NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

A MODEL-BASED ARCHITECTURE APPROACH TO SHIP DESIGN LINKING CAPABILITY NEEDS TO SYSTEM SOLUTIONS

by

Jillian E. Bahlman

June 2012

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE A Model-Based Architecture Approach to Ship Design Linking Capability Needs to System Solutions			**5. FUNDING NUMBERS**
6. AUTHOR(S) Bahlman, Jillian E.			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ______N/A______.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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For demonstration of this approach, a simple design reference mission is created and a functional architecture is described. The capability of a potential design solution (assumed to have the physical architecture of a ship) is modeled to evaluate logical behavior and mission effectiveness. These models aid in the formation of physical design specifications, which are incorporated as inputs to a ship synthesis model. Several alternatives can be created for comparison that reveals the costs associated with various levels of capability giving decision-makers to ample information to consider.

14. SUBJECT TERMS Model-based systems engineering, functional architecture, capability-based design, ship design, tradeoff analysis			**15. NUMBER OF PAGES** 119
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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A MODEL-BASED ARCHITECTURE APPROACH TO SHIP DESIGN LINKING CAPABILITY NEEDS TO SYSTEM SOLUTIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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LIST OF ACRONYMS AND ABBREVIATIONS

DRM	Design Reference Mission
MBSE	Model Based Systems Engineering
AAW	Anti-Air Warfare
MOE	Measure Of Effectiveness
DES	Discrete Event Simulation
HM&E	Hull, Mechanical, and Electrical
MOP	Measure of Performance
OPSIT	Operational Situation
ASM	Air-to-Surface Missile
SLC	Small Littoral Combatant
UNTL	Universal Naval Task List
I&W	Indications and Warnings
EFFBD	Enhanced Functional Flow Block Diagram
NATO	North Atlantic Treaty Organization
EM	Electromagnetic
LP	Loop
IFF	Identification Friend or Foe
SM	Standard Missile
NSSM	NATO Sea Sparrow Missile
RAM	Rolling Airframe Missile
CIWS	Close-In Weapon System
3D	Three Dimensional
P_s	Probability of Survival
P_{Hit}	Probability of Hit
SAM	Surface-to-Air Missile
P_k	Probability of Kill
OPV	Offshore Patrol Vessel
SSDG	Ship Service Diesel Generator

CIC	Combat Information Center
SWBS	Ship Work Breakdown Structure
Ltons	Long Tons
VLS	Vertical Launching System
ASW	Anti-Submarine Warfare
ASuW	Anti-Surface Warfare

ACKNOWLEDGMENTS

The author wants to thank Professor Whitcomb for his inspiration and guidance in performing this study. Appreciation must be expressed towards Mrs. Mary Vizinni for meticulously reviewing this paper and ensuring its readability from an academic perspective.

To her family, who has shown patience and support through this process, the author is grateful. Especially to her father, Mr. Joe Bahlman, whose endless interest in her studies was a constant encouragement and his volunteering to read a draft provided valuable feedback on readability from a non-engineering perspective.

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I. INTRODUCTION

This thesis examines ship design that incorporates system architecture development and model-based systems engineering (MBSE); it features a method of moving from desired capabilities needs set by the U.S. Navy and working towards the design of a ship. This top-down ship design perspective examines a design space, specifically the tradeoffs between mission effectiveness and ship performance and cost.

The initial capability needs of this ship design process are translated to requirements and incorporated into a design reference mission (DRM) upon which further design decisions are based. The DRM includes a description of the missions that the system will be expected to perform, how mission effectiveness will be measured, and how well the system should perform in the missions.

With capabilities and a DRM documented, the ship's functional architecture can be created. The requirements are allocated to functions (in the form of verb statements) that the ship will perform. Each of those functions is decomposed into sub-functions to create a functional architecture as a hierarchy for the entire ship. Functional allocation, mapping general physical components to each of the functions in the hierarchy, is done to makes up the ship physical architecture. Specific criteria for the elements (components) of the physical architecture are determined through the coupled mapping of mission effectiveness and ship synthesis modeling.

Once the ship is described in terms of requirements, functions and physical components, a behavioral model is created to describe how the ship will act in a particular scenario, such as anti-submarine warfare (ASW), Anti-Air Warfare (AAW), anti-surface warfare (ASuW), etc. For this thesis, the scenario used to demonstrate a behavioral model is AAW. The AAW behavioral model shows how the ship will respond in terms of functions that will be performed, the sequence in which they will be performed, as well as, triggers, inputs, and outputs. As in all mission areas, there are many variables that determine the exact course of action taken by a system. These possibilities are all displayed in the behavioral model as logic gates and symbols.

Verification is performed on the model through a resource-monitoring simulation. To demonstrate this verification, the limited resource in question is the time it takes for a scenario to run and the duration of functions. The scenario time is determined by the time it takes a missile to reach the ship from the point it was launched. All necessary functions must perform their tasks in sequence within that finite time.

After it is established how the ship will act in a scenario then the quality of performance can be designed by selecting the individual system physical component. A discrete event simulation (DES) model is created based on the behavioral model and the physical architecture. Quantitative measures of effectiveness (MOE) are used to describe how well the ship performs in an AAW scenario. With variable input parameters included in the model, optimal design criteria can be determined. In this AAW scenario, the radar detection range will be varied in the simulation to determine which range returns the desired MOE outcome. That desired radar detection range then becomes a design criterion for the combat system of the ship. When designing the ship layout and characteristics, a radar system will be selected that meets the radar range criterion.

For this thesis, a ship synthesis model is used that accounts for the radar system parameters (i.e., weight and power usage) as a function of desired radar detection range. The characteristics of a reference ship of similar mission and approximate size are used as a starting point for synthesis. Other input values to the synthesis model correlate to requirements through the physical and functional architectures. The output is a list of various characteristics of the ship such as dimensions, weight, combat systems suite, and cost.

The ultimate goal of this work is to provide an example of a design trade space that reflects the cost of performance in terms of a single mission area, in this case AAW mission effectiveness. The trade space will provide decision-makers with options and information with which they can make thoughtful decisions. Furthermore, this approach can be generalized to any mission area to allow for traceability between all stages of design back to the initial DRM and system capability needs.

A. BACKGROUND

A naval surface combatant ship is a very complex system from an engineering design perspective. Challenges in this field are numerous. These challenges are present in the form of financial and technological issues, not to mention that creation of the right design solution for an uncertain future threat environment is a difficult task. For classes of ships designed for two or three decade service lives, there is risk that the projected threat environment will change within that time. With the goal of reducing cost and project lead-time and ensuring delivery of capabilities-appropriate design solutions, the Navy is in constant search of ways to improve the outcomes.

The United States has been in the business of ship design since the country was just starting out. By way of the Naval Act of 1794, the U.S. Navy came to life with the construction of six frigates. In those days, shipbuilders were government employees. As time went on, technology improved and potential threats to the nation and its interests relied increasingly on a strong naval force. In 1866, the Navy established a Construction Corps of Naval Officers who would receive specialized training and education in the field of ship design and construction. Just before World War II, the Construction Corps was completely disbanded, which put warship design into the hands of civilian naval architects who were employed by the Naval Sea Systems Command (Ferreiro, 1998). Since then, building new warships became not only the business of the government but also a market for industry.

Constant evolution of the fleet is necessary to keep up with the ever-changing threat environment. The long history of naval ship design has lead to a paradigm in which technological complexity is an inevitable necessity to achieve suitability in the world's maritime theaters of today and tomorrow. Both cost and effectiveness measures must be met in a final design, which is comprised of the integration of many subsystems (Whitcomb, 1998).

1. Integration

The existing process for designing ships in United States Department of the Navy has a recent record that shows the design process tends to take longer than expected and more money than planned while allowing for compromised performance and shortfalls in capabilities (Fox, 2011). Design teams for projects as large as a new naval surface combatant are split up into groups within groups of engineers, managers, analysts, and government or military representative overseers. The workload is then divided among the major groups to accomplish the task of designing a ship in pieces. One major group is responsible for designing the hull, mechanical, and electrical systems (HM&E). Another major group is tasked with design of the combat systems (or mission systems). While this approach of divide and conquer may seem to be the most intuitive, the complex nature of naval combatants requires early and frequent considerations for integration, which is not an easy task for independent groups. Traceability of system requirements, limitations, and constraints are not clear between the work projects of all design groups. Thus, inevitably, as the pieces are brought together, they do not fit perfectly and compromises have to be made, yielding a less than ideal design solution.

MBSE tools such as *CORE* provide for identification and mapping of interfaces, mapping of needs to requirements to solutions, and provide a cohesive and consistent system model upon which to base the design process.

2. Validation

Validation is making sure that the system being designed is the right solution for the needs of the stakeholders. When the operating environment of the system is projected, the ability of the system to combat future threats can be simulated. Modeling and simulation tools such as *ExtendSim* and *CORESim* aid in the exploration of performance parameters necessary to satisfy the capability needs, which link the capability needs to the end solution.

B. LITERATURE REVIEW

This thesis follows the work of three studies into the ship design process. Welch (2011) examined a method to supplement current combatant ship synthesis tools with combat system equipment and war fighting capability parameters. This method laid the groundwork for creating an improved ship synthesis tool that includes complete sensitivity to capabilities from all combat systems on the ship and how these selected parameters impact mission performance in a large spectrum of warfare areas.

Fox (2011) developed a methodology for the design of a warship that is capable of showing how naval architecture related decisions interact with operations measures of effectiveness through the use of modeling and simulation. With this method, decision makers can assess various system outcomes by trading off performance parameters to make capability-based decisions.

The work done by Szatkowski (2000) proposed a methodology based on axiomatic design principles to eliminate the currently accepted iterative nature of concept level ship design. He studied the design at each level of the hierarchy to determine the logical order to fulfill each requirement such that these couplings do not adversely impact the design progression. By implementing this methodical approach, the ship design process followed a repeatable structured format in which functional relationships between physical parameters are mapped, documented, and controlled.

The work done in this thesis will link together the architecture development method from Szatkowski with the tradeoff analysis of Welch and Fox.

C. RESEARCH QUESTIONS

The need for meeting future naval capabilities that result in appropriate system solutions necessitates a long and expensive process of engineering and test and evaluation. This thesis attempts to discover how a structured model-based approach can provide a consistent basis for connecting capability need to the end solution. Further, it asks, “How can a ship be designed effectively in terms of performance and effectiveness

related to mission capabilities? In what ways can modeling tools promote the creation of the right design solution in terms of performance and effectiveness related to mission capabilities?"

MBSE is a method in which system-level models are used to simulate functions and evaluate capabilities: in Sala-Diakanda (2004) MBSE is described as "the formalized application of modeling to support systems requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." With this definition in mind, this research seeks to uncover how MBSE can be used to enhance traceability throughout a combatant ship design process to produce a valid trade-space for decision-makers. MBSE will be used to demonstrate how the quantitative results of a tradeoff between ship characteristics, such as displacement and cost, and mission effectiveness can be used to reason about the engineering possibilities involved.

D. MODEL-BASED SYSTEMS ENGINEERING APPROACH

This thesis is a MBSE approach to ship design because it centralizes computer models for the major steps in the systems engineering process. As stated by Estefan (2007), "model-based engineering is about elevating models in the engineering process to a central and governing role in the specification, design, integration, validation, and operation of a system."

This thesis uses the term "system" as a placeholder for a solution to the need. As described in ISO/IEC/IEEE 42010 (http://www.iso-architecture.org/ieee-1471/faq.html), an international standard for development of system architecture descriptions, a system could refer to an enterprise, a system of systems, a product line, a service, a subsystem, or software. All systems have architectures whether they are documented or not as they are the conception of a system. The Standard defines architecture this way: "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design." The purpose of developing an architecture description is to aid in the understanding, analysis, and comparison of systems as well as determine the system's form, function, value, cost, and risk. Figure 1

captures key terms and concepts of systems and their architectures. The various relationships between the architecture model, system, stakeholders, and environment are illustrated.

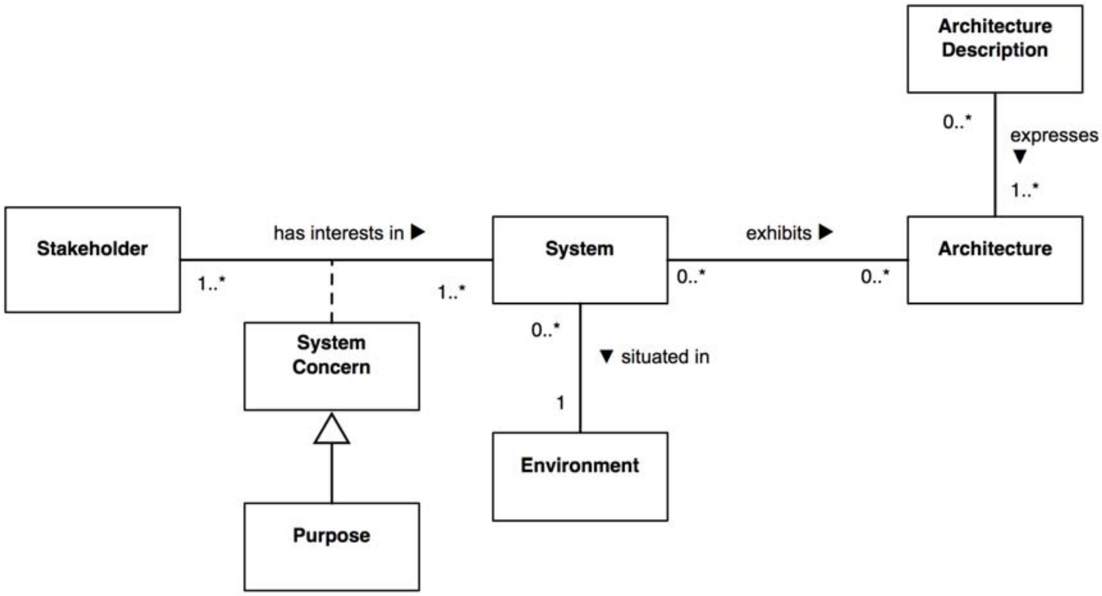

Figure 1. System Relationships Diagram

A process model is used to guide the analysis, design, development, and maintenance of systems. There are many methods and techniques used to direct the life cycle of a system development project. Most real-world models are customized adaptations of generic models (Center for Technology in Government, 1998). Figure 2 shows a developmental process model commonly used in systems engineering. Each step includes a degree of iteration and checking for validation and verification. A MBSE approach might follow a general process model much like this, however, each activity will be accomplished through the development of models, and the iterations of which will be of increasing detail and accuracy.

Using the “Vee” model as an example, Figure 2, the first process activity is “Understand user requirements, develop system concept, and validation plan.” For designing a surface combatant in this thesis, that step is accomplished using the modeling

and simulation tool, *ExtendSim*. The second block in the "Vee" model is "develop system performance specifications." The modeling program *ExtendSim* and *CORE* will be used to perform this activity.

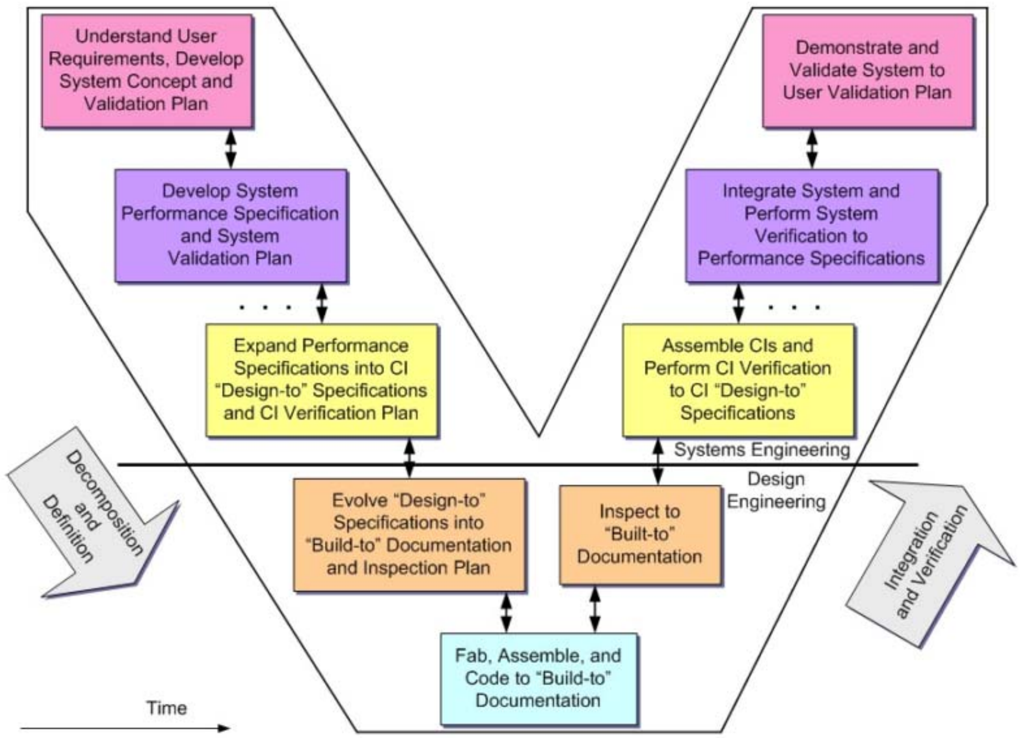

Figure 2. Systems Engineering Process Model (From Estefan, 2007)

E. METHOD

The steps that make up this method allow for multiple iterations and various outcomes on which to base a design space for exploration allowing decision-makers to select a preferred solution based on design, performance, and cost. The method incorporates detailed traceability throughout all steps, which makes early-and-often validation and verification apparent.

The products of the major steps of this method are to create a DRM, functional architecture, and physical architecture; to conduct behavioral modeling and effectiveness modeling, and to accomplish finally the synthesis of a ship. As each product is being

developed the previous step(s) could be affected. This is primarily a recipe that depends on a great deal of re-evaluation of past products and iteration for validation and verification.

To form a MBSE approach, modeling and simulation tools are used to create the products. The modeling environment software, *CORE*, is used to develop the functional and physical architecture of the combatant ship and to simulate and verify the ships behavior in scenarios. The DES modeling software, *ExtendSim*, is used to evaluate the system's performance and effectiveness for particular threat scenarios. Ship synthesis is conducted within an *Excel* model. Together, these tools will enhance validation and traceability of system requirements throughout the process of designing a complex surface combatant.

This thesis offers a small-scale demonstration of all these complex system design steps using simple example scenarios and parameters. For example, focus will be applied to only one major combatant mission area—AAW, and is evaluated based on a single measure of effectiveness (MOE)—the probability of survival in a missile threat scenario. The method scales up to more authentic ship designs.

F. SCOPE OF THIS THESIS

The scope of this thesis is primarily intended to demonstrate a proposed method for accomplishing the task of designing a ship and presenting alternatives for analysis in a trade-space. The models used for this demonstration are straightforward so as not to convolute the intent of this study. In a real-world naval combatant design project, the models would be replaced with more detailed ones, though the tools—particularly *Extendsim* and Vitech *CORE*—could be used in real-world combatant ship design projects. Any recommendations made from this thesis will refer to the methodology and use of modeling and simulation rather than to the analysis of the example model itself.

G. BENEFITS OF THIS STUDY

The intent of this thesis is to demonstrate a method and evaluation that might offer new insights into how MBSE can be used to improve the combatant ship design

process. Through demonstration of a process in which alternative conceptual combatant designs can be created with a greater degree of traceability from the top down and analyzed for trade-space considerations, the foundation for incorporating MBSE in combatant ship design is demonstrated.

II. DESIGN REFERENCE MISSION

The DRM defines the projected threat and operating environment upon which a rigorous systems engineering process can be based. The intent of a DRM is to ensure that the system being developed will meet the Navy's needs. Following the guidance of Skolnick and Wilkins (2000), a DRM is presented in the form of "specific operationally representative situations and supporting threat and physical environment characterizations." The operational situations (OPSIT) are intended to describe operational characteristics of the system in a combat environment for which it is to be designed.

When DRMs are created for application in a real world project, inputs and reviews are taken from the communities that would use the system as well as the acquisitions and intelligence communities. Stakeholder input is essential to ensuring valid, realistic, useful solutions (Skolnick & Wilkins, 2000). For the purposes of this thesis analysis, all threat and mission information is notional.

A. ANTI-AIR WARFARE MISSIONS

AAW is a major mission area of surface navies. This thesis focuses on AAW because the mission lends itself nicely to straightforward implementation using DES modeling, and the author has professional and academic experience on the subject. It encompasses the tasks to search, detect, track, classify, and neutralize hostile airborne targets. A battle group working together or an independent ship could perform these tasks. Many integrated systems are involved in carrying them out. Ship borne systems such as three-dimensional air search radars (e.g., SPY-1) and electronic signal detectors (e.g., SLQ-32) are used to detect and detect airborne contacts. Additionally, the Navy has many surface-to-air weapons and counter measures to use to neutralize airborne threats.

The targets in an AAW scenario are either Air-to-Surface Missiles (ASM) or enemy aircraft. Targets can be neutralized in two general forms. The first is what is

known as a “hard kill” where the airborne target is physically destroyed. Hard kills are achieved by hitting the target with a missile or gun system (e.g., SM-2 or CIWS). A “soft kill” is when the missile or aircraft is prevented from hitting the ship by methods other than destruction. Soft kills can be achieved through the use of electronic countermeasures, such as chaff or active jamming.

B. OPERATIONAL SITUATION

The context in which AAW is applied is simplified for the purposes of clear demonstration of the method in this thesis. The ship operates independently with its one sensor, air search radar, to detect an in-bound enemy aircraft that releases a single ASM. The goal of the ship is to detect the aircraft and/or the missile. The only methods for kill in this simplified scenario is hard kill via surface to air missile (SAM) or Close in Weapon System (CIWS). If the ship only detects and classifies an enemy aircraft it will try for a hard kill. However, if the ship detects both aircraft and ASM it will engage only the ASM because it is assumed that the enemy aircraft will retreat once it has released its weapon.

1. Mission Profile

This notional scenario is intended to be simplistic yet feasible for a real world engagement. Within ten years from now hostilities arise between the U.S. and an unspecified adversary. The Navy has requested that an asset be positioned off the western coast of the Korean Peninsula in the Yellow Sea. Analysis of collected intelligence has determined that an airborne attack on any U.S. asset in the area is imminent. It is assumed that the Fleet Rules of Engagement allow a commanding officer to defend his or her ship and crew from any attack without waiting for approval. As the date and time of the attack are anticipated, the ship makes all preparations for battle. The general quarters watch stations are manned; in other words, the asset and its crew will be at its most heightened state of readiness. The commanding officer has issued a preemptive order to immediately engage any target classified as enemy so that maximum time is allowed for SAM to travel.

2. Threat Characterization

The ASM missile in this mission profile has characteristics resembling those of the French-made Exocet anti-ship missile (AM-39). Figure 3 shows an Exocet missile fixed to a French-made Dassault Rafale fighter aircraft.

Figure 3. Exocet AM39 (Photo by D. Monniaux, from Wikipedia)

Table 1 lists some of the characteristics of the Exocet missile (See http://www.missilethreat.com/cruise/id.5/cruise_detail.asp).

Table 1. AM-39 Exocet Missile Characteristics

Characteristic	Value
Country	France
Target	Ship
Length	4.69 m
Diameter	0.35 m
Wingspan	1.1 m
Launch Weight	670 kg
Payload	165 kg HE, fragmentation
Propulsion	Solid
Range	50-70 km
Guidance	INS, active radar
In service	1979-Present
Exported	Argentina, Brazil, Egypt, Greece, India, Iraq, Kuwait, Libya, Oman, Pakistan, Peru, Qatar, Saudia Arabia, Singapore, South Africa, UAE, Venezuela

The threat aircraft used to deploy the ASM is similar to the Dassault Rafale, as shown in Figure 4.

Figure 4. Dassault Rafale Multirole Fighter (From French Defense Ministry Website)

3. Physical Environment

The mission profile in this DRM takes place in the Yellow Sea. The area has a large amount of fishing and commercial shipping traffic. Commercial air traffic is moderate in the airspace over the Yellow Sea. The area has very cold winters with monsoons. Summers are rainy and warm with frequent typhoons. Fog is very common along the coasts and the water depth is very shallow on average, approximately 44 meters.

C. MEASURES OF PERFORMANCE AND EFFECTIVENESS

A MOE is, as stated in the Defense Acquisition University Glossary, a measure designed to correspond to accomplishment of mission objectives and achievement of desired results. An MOE can be mapped to MOPs.

The Universal Naval Task List (UNTL) includes measures and criteria that the Navy uses to assess the tasks performed by naval assets (CNO, CMC, & HUSCG, 2007). Task number 3.2.7, "Intercept, Engage, and Neutralize Enemy Aircraft and Missile Targets (Defensive Counter Air)," has three measures of performance. Table 2 shows the MOPs listed for this task.

Table 2. UNTL Task 3.2.7 Measures of Performance

Index	Form	Measure Description
M1	Number	COA denied to enemy due to friendly interdiction
M2	Percent	Of enemy targets engaged.
M3	Percent	Of targets attacked with desired effects.

While the task 3.2.7 MOPs would provide valid evaluation of an offensive task, the mission profile in this thesis describes a countertargeting situation. The task description of task number 3.1.7 is "Employ countertargeting tactics when either the tactical situation warrants or when indications and warnings (I&W) indicate an attack is imminent. I&W must permit sufficient time to put countertargeting assets in place." The measures of this task are listed in Table 3 (CNO et al., 2007).

Table 3. UNTL Task 3.1.7 Measures

Index	Form	Measure Description
M1	Percent	Of units successfully countertargeted.
M2	Time	To initiate countertargeting
M3	Percent	Of casualties sustained after countertargeting initiated.

The MOE in this mission profile is the survivability of the ship. The MOP that will help determine the MOE is the probability of survival against the ASM threat. Task 3.1.7 M3 (percent of casualties sustained after countertargeting initiated) is how the performance of the ship will be evaluated for this DRM and will be stated as the probability of survival (P_S).

D. SYSTEM REQUIREMENTS

The customer, user, and primary stakeholder for this demonstrative design project are the U.S. Navy. The process for determining and selecting a physical architecture alternative for which to explore mission effectiveness is to perform a capabilities-based analysis to determine capability gaps. Then, do a solution neutral simulation of mission needs, use it for the functional system architecture description and determine the functional specifications necessary to accomplish the mission. Physical architectures of various solutions will be mapped to the functions. For this thesis, it is assumed that the physical architecture of “ship” is best. Therefore, the alternatives created for comparison will all be ships.

For this thesis a fictional need and capability gap will be evaluated based on the assumption that a maritime asset, namely a surface combatant ship, may be a feasible solution. In this mission profile, the country wants presence of military power in the Yellow Sea area to deter the adversary from performing any hostile acts against the United States and its allies.

It is further assumed that at this time a platform that can support this mission in that particular environment does not exist. The specific capability gap that prevents an existing system from performing this mission lies in the AAW mission area and sustained independent operation in littoral waters. The fictional capability gap used for demonstration in this thesis is the ability for the future conceptual ship to defend itself from enemy airborne attack.

E. CHAPTER SUMMARY

This chapter established the missions that the ship will be expected to perform, the expected environment of operation, the threats, and the MOEs. It is assumed that a feasible alternative to meet future defense needs is a ship that can operate independently in a shallow area where it will likely not be resupplied for up to a month, and there is risk of enemy attack with ASMs. All subsequent design decisions will be traced back to this DRM.

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III. ARCHITECTURE DEVELOPMENT

This approach to model based systems engineering for combatant ship design utilizes one modeling tool for architecture development. A comprehensive integrated modeling environment within the software program, Vitech *CORE,* has many features that are useful for engineering a complex system. These features include, but are not limited to, requirements management, behavior analysis, architecture development, and validation and verification.

This tool along with a ship synthesis model provides complete end-to-end traceability. Capability needs and requirements delineated by the Navy are traced to the functional architecture, then mapped to a physical architecture. The specific characteristics of the physical components can be manipulated within the realm of feasibility to satisfy operational effectiveness requirements, which are then implemented in ship design alternatives.

A. FUNCTIONAL HIERARCHY

The functional architecture of a surface combatant describes what the system needs to do, as opposed to how it will do it, in order to satisfactorily perform as intended. This description is phrased in terms that leave the solution undetermined, otherwise referred to as solution independent, so that engineers are not limited by or aiming for a predetermined design (aside from the assumed constraint that the solution will be a ship). The architecture is built from the top down or in other words starting from the top-level essential functions, which are decomposed by sub-functions.

The combatant functional architecture used in this thesis follows the work of John Szatowski (2000), which analyzes the functional hierarchical decomposition of a naval surface combatant based on functional requirements, which are mapped into physical design parameters. This functional architecture includes six top-level functions that are the requirements common to all seagoing vessels as well as those relevant only to

warships. These top-level functions, as modeled in *CORE*, are displayed in Figure 5 as a decomposition of the system level requirement "Perform Surface Combatant Missions."

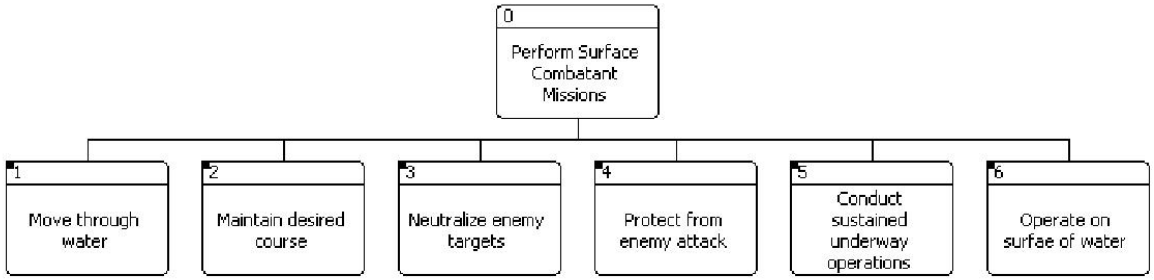

Figure 5. Top-level Functions of a Surface Combatant

Each top-level function is then decomposed into levels of sub-functions. The functional hierarchy is comprised of all solution independent verb statements to indicate the actual actions that take place to satisfy the function they are decomposing. The sub-function numbers are referenced to their parent functions and are not indicators of execution order or importance. Figure 6 is an example of the second-level decomposition of a top-level function. The remaining second-level functional hierarchies are included in Appendix A. Appendix B contains a table of all the functions mapped to their respective physical components.

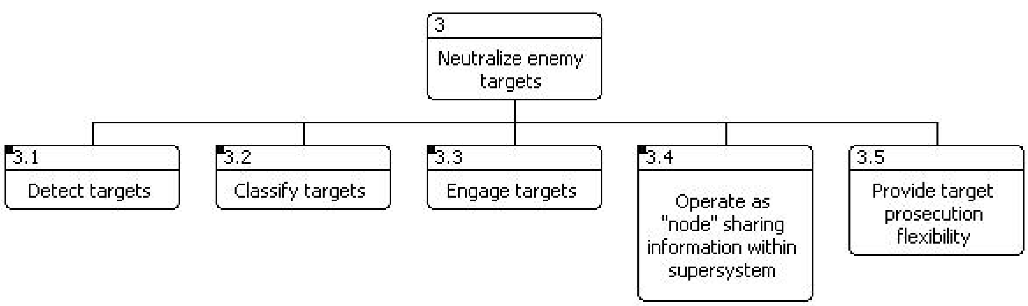

Figure 6. Second-level Functional Decomposition of Function 3

B. PHYSICAL HIERARCHY

Each element of the functional hierarchy is allocated to a physical component. These components will comprise a hierarchal decomposition that mirrors that of the functional architecture. Table 4 shows the top-level functions and the physical components to which they are allocated. This thesis follows Szatkowski in that a one-to-one allocation design was used. That is, each function is allocated to exactly one component. The numbering scheme for the functional hierarchy and the physical components are identical. This method clearly illustrates traceability between the two architectures, which is a primary objective of this thesis.

Table 4. Top-level Functions Mapped to Components

Number	Function	Component
0	Perform Surface Combatant Missions	Ship
1	Move through water	Propulsion system
2	Maintain desired course	Maneuvering and control system
3	Neutralize enemy targets	Combat systems configuration
4	Protect from enemy attack	Countermeasures methods
5	Conduct sustained underway operations	Support/Auxiliary systems
6	Operate on surface of water	Hull form

In some cases, typically for the higher levels of the hierarchy, the physical component is an entire subsystem. To allow designers flexibility and to maintain a degree of solution independence, the component descriptions are kept very general. They may provide an example system that performs the allocated function but they do not indicate placement, quantity, or specific characteristics. Mission effectiveness modeling and ship synthesis modeling will determine those details. As in the case of the function "Neutralize long range airborne weapons," the allocated component is "Long range surface to air missile system" with the example system provided, NATO Sea Sparrow.

A complete table of the entire mapped functional and physical hierarchies is included in Appendix B.

C. BEHAVIORAL MODEL

Behavioral models are used to describe possible patterns of behavior for the system. System architects use behavioral models to illustrate complex system relationships and dynamic possibilities so that clients and builders can understand the relationships between functional elements and likewise between physical elements. Because behavioral models are meant to show a system's behavioral processes, the level of detail in a model is determined by what a client will likely be able to understand. In this case, the functional blocks chosen correspond to the level of detail with which naval personnel are familiar.

1. Enhanced Functional Flow Block Diagram

The behavioral model used in this thesis is an Enhanced Functional Flow Block Diagram (EFFBD). It provides a basis for establishing multi-layered processes with sequential, parallel, repetitive, and decision logic used show how the system behaves (Vitech Corporation, 2011). Threads illustrate a system's functional response in a particular event. For a surface combatant, an anti-submarine warfare scenario might begin with the detection of a target followed by classification and engagement.

Each function block in the EFFBD can have associated attributes such as inputs, outputs, triggers, resource utilization, and time durations. These input, output, and trigger attributes further describe the interaction between function blocks and show the client how the system works.

Resource utilization and time duration attributes help the engineers to determine feasibility and limitations of the system. For example, in this EFFBD, an incoming ASM has a velocity and a detection range, which translates to a finite and predictable time to impact. If the components allocated to the functions in this scenario cannot perform their tasks within that time limit, then the system will be ineffective. A stochastic operational model using estimated system performance, probabilistic responses, and a randomized item generation enhances the warfare effectiveness study. This thesis utilizes a modeling

tool called *ExtendSim* to trace the functional and physical architecture to mission effectiveness, which is discussed in the section titled “Mission Effectiveness.”

2. Anti-Air Warfare Scenario

The scenario modeled throughout this thesis is an AAW scenario. The surface combatant of this project has functions that allow it to detect, classify, and engage airborne targets. Action options are presented to the systems in the form of OR-gates, AND-gates, loops, and iterations. Specific scenario parameters are what determine which response the system will take. The EFFBD does not include every possible outcome; rather it demonstrates the logic flow of the function blocks.

In this model, an airborne target is detected and then it is classified as either an enemy aircraft or an ASM. If it is an enemy aircraft, the missile launch system will be activated and a missile will be launched. The launch will trigger the system to track and guide the missile to the target. If, at that time, the aircraft is still flying inbound, the system will complete the loop: otherwise, the scenario is over. In the case where the system initially detects an inbound ASM, one of three weapon systems will be chosen, depending on the ASM range. The weapon system selection and engagement will loop continuously until the ASM is killed or the ship is hit, at which time the scenario is over.

3. Anti-Air Warfare Enhanced Functional Flow Block Diagram

The functional blocks used to demonstrate how the system operates in this scenario were chosen based on what a person in the Navy would understand. For example, the first block was chosen to be “Detect airborne targets” rather than the functional blocks it is decomposed by, “Switch between transmit/receive, “Transmit/receive EM pulse,” and “Process EM data” because the words “Detect airborne targets” is the level of rigor with which the action is commonly associated.

Figure 7 shows the portion of the AAW EFFBD that depicts the system options once an enemy aircraft has been detected. This EFFBD diagram shown is a product of the modeling software, *CORE*, by Vitech. The blocks are each labeled with their unique numerical identifier, the function in the form of a verb statement, and the allocated

physical component. Functional flow logic is depicted by circled words or abbreviations such as “OR,” “AND,” “LP,” and “EXIT.” The word “OR” serves as an exclusive OR-gate where exactly one branch will be executed. The branches following a circled “AND” are parallel actions which, will all be executed. “AND,” “OR,” and “LOOP” logic streams will repeat the circled word at the end of the set of function blocks. An “EXIT” represents a scenario termination.

As shown in Figure 7, the function stream begins with “Detect airborne target” and then a circled “OR” splits the stream into two branches. The top branch represents the case when the detected target is only an aircraft and the lower branch is for when an ASM is detected. In this scenario, if an enemy aircraft is inbound it is assumed that it is entering a range in which an ASM can be deployed. The purpose of the top branch is to kill the aircraft before it has the opportunity to drop a weapon. The aircraft will not be engaged if it has already dropped its weapon, rather the ship will begin to engage the inbound ASM. Following detection of only an aircraft, it will be classified electronically, using a physical component such as the Identification friend or foe system (IFF).

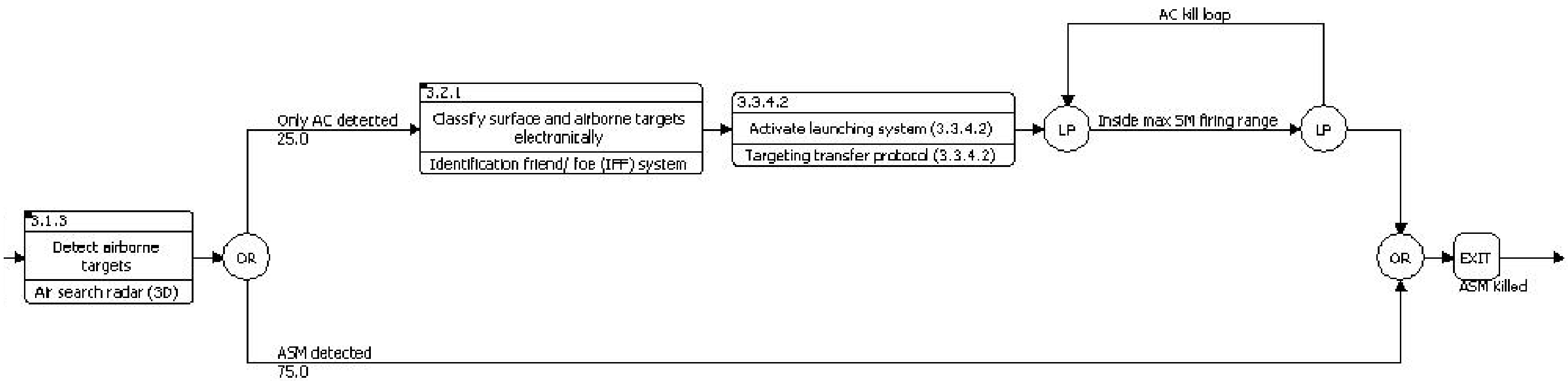

Figure 7. AAW EFFBD (Only Aircraft Detected)

Upon completion of an enemy classification (as illustrated in Figure 8) the ship will activate its launching system, then wait for the aircraft to enter the maximum standard missile (SM) firing range, which is when the "aircraft kill loop" begins. The first function that is included in the kill loop is "Launch Missile." From this function, a circled "AND" represents the parallel functions: "Guide missile to target" and "Track missile's flight path," which both occur simultaneously. As the ship tracks the missile's flight path, there are three possible options. The first is that the aircraft was not killed, it is still in firing range, and an ASM was not deployed. The second option is that the aircraft was not killed; however, it did drop an ASM, for this case the aircraft kill loop will be exited so that the ship can begin prosecuting the ASM. The third option after the launch of the first SM is when the aircraft was killed and the scenario is ended.

A complete illustration of the "Only aircraft detected" branch and the "ASM detected branch are included in Appendix C.

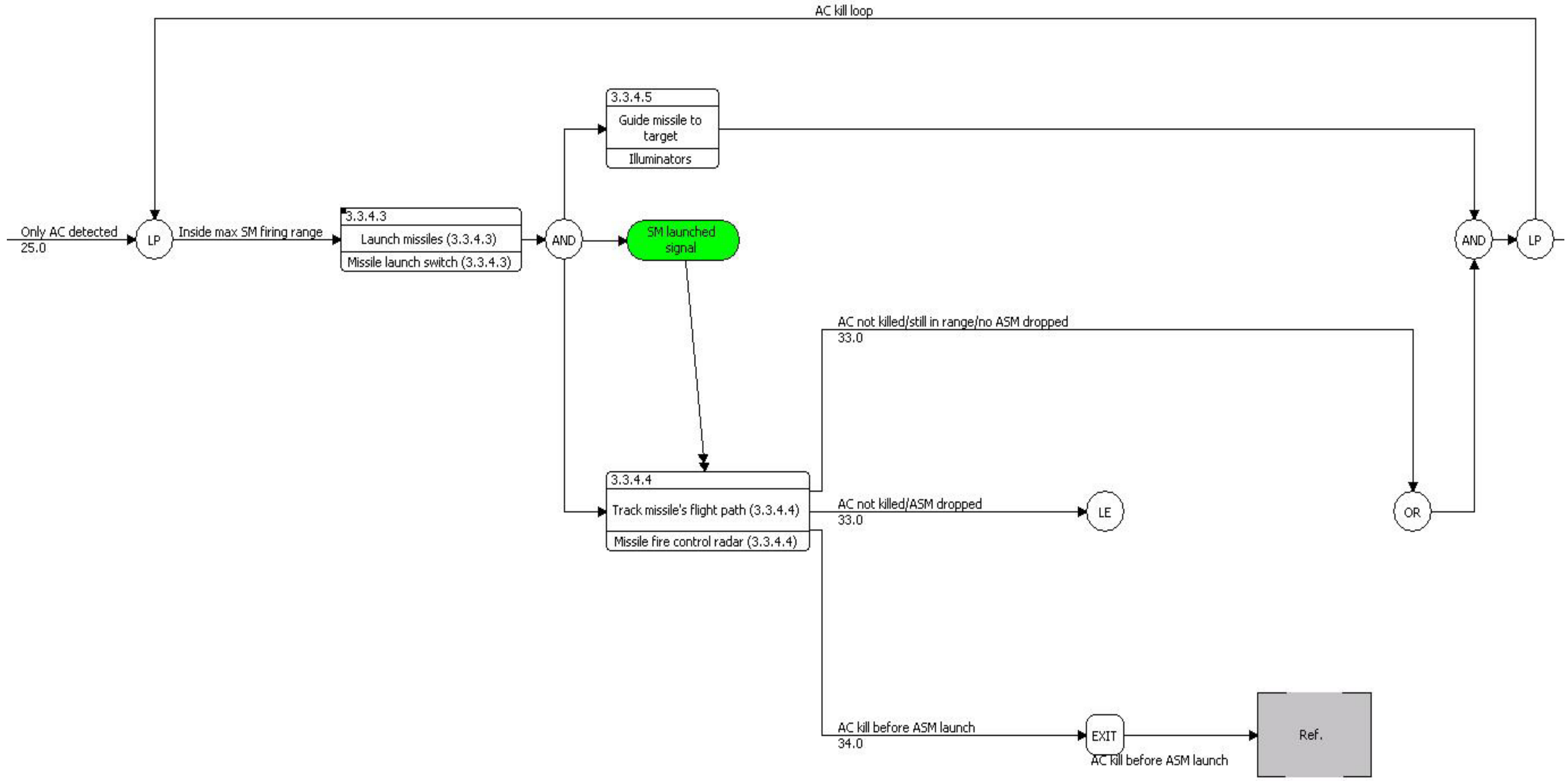

Figure 8. AAW EFFBD (Aircraft kill loop)

The second branch exiting from the first function, “Detect airborne targets,” is to cover the instance when the target detected is an ASM. The exclusive OR-gate comes immediately after the detection of target rather than after the classification function box because the 3D air search radar system can make the determination of aircraft or missile based on velocity and trajectory. The classification function is intended to determine whether the detected aircraft is an enemy or a friendly force. The “ASM detected” branch needs no similar friend or foe classification function because all high speed inbound missiles will be assumed a threat and prosecuted. Figure 9 shows the branch split following the detection of an airborne target. Once an ASM is detected, the ship enters the ASM kill loop where it will determine if the ASM is inside the engagement window.

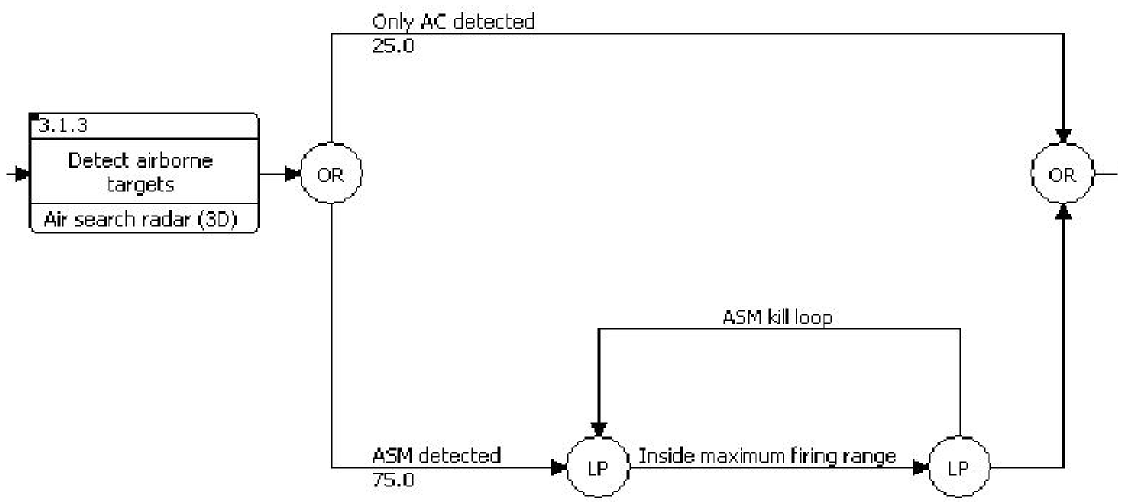

Figure 9. AAW EFFBD (ASM Detected)

Inside the ASM kill loop the ship is presented with three options of an exclusive OR-gate. Depending on the range of the ASM for a particular iteration of the loop, the ship can utilize its weapon system that is intended to neutralize long, medium, or short-range airborne targets. The corresponding sample physical systems for these functions are the NATO Sea Sparrow Missile (NSSM), the Rolling Airframe Missile (RAM), and the Close In Weapon System (CIWS), respectively. Figure 10 shows the first two selection possibilities, long-range and medium-range weapon systems. Both options

include functions for activating the weapon system, launching missiles, tracking, and guiding the missile to the target. At the end of each option, a kill evaluation is made that determines whether the ASM kill loop is repeated or if the scenario is ended, denoted by a circled "EXIT." When a kill evaluation determines that the ASM was not killed and the loop must be repeated, the ship will be presented with the option of weapon systems again depending on the new ASM range.

Figure 11 shows the third weapon system option. The function "neutralize short-range airborne targets" (such as CIWS) will be selected if the ASM range is within the engagement window. This branch represents the last line of defense for the ship. Three outcomes are possible once the ASM is engaged by the CIWS. The first possible outcome is the ASM is not killed and the target is still inside the engagement window so it will continue the ASM kill loop. The second outcome is that the ASM is killed and the scenario is over. The third possible outcome is the case when the ASM is not killed and it is no longer inside the engagement window, meaning the ship has been hit and the scenario is ended.

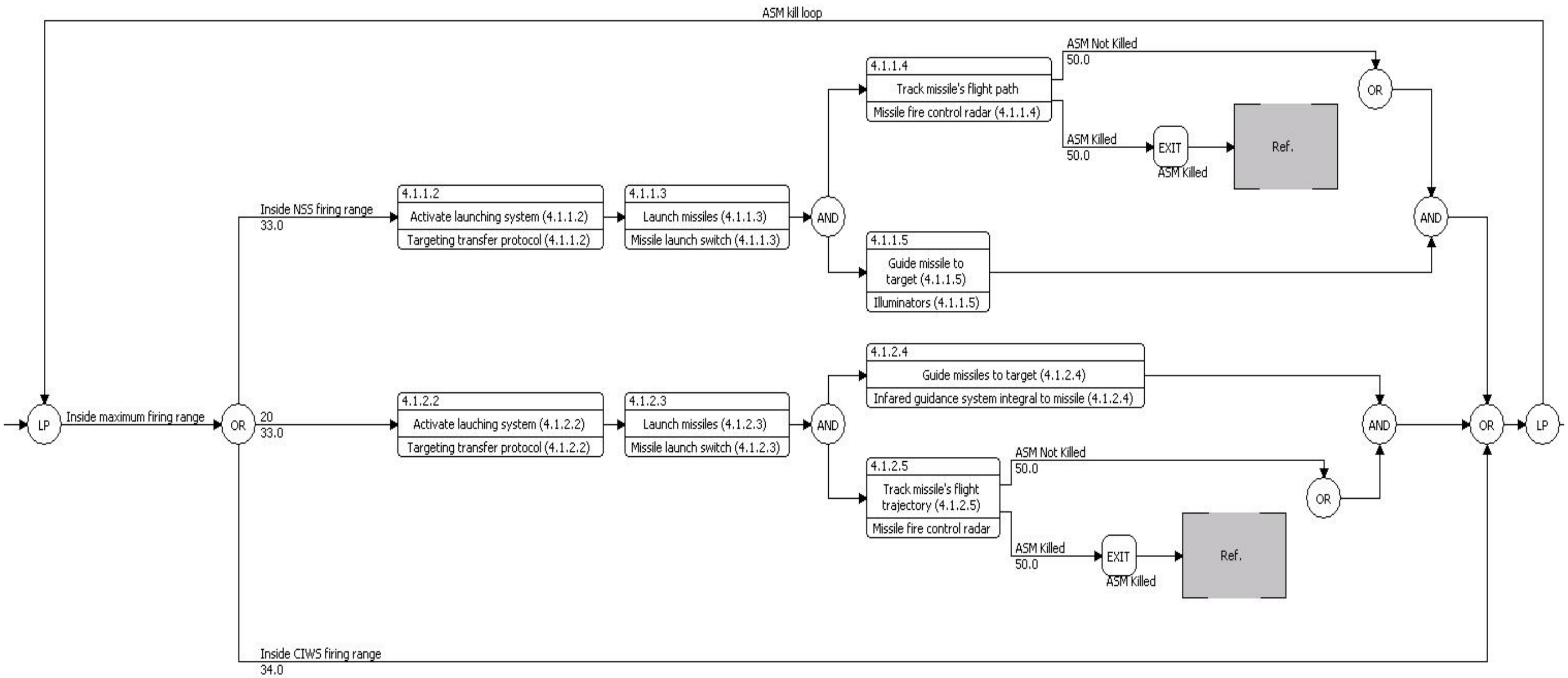

Figure 10. AAW EFFBD (ASM kill loop) Part 1

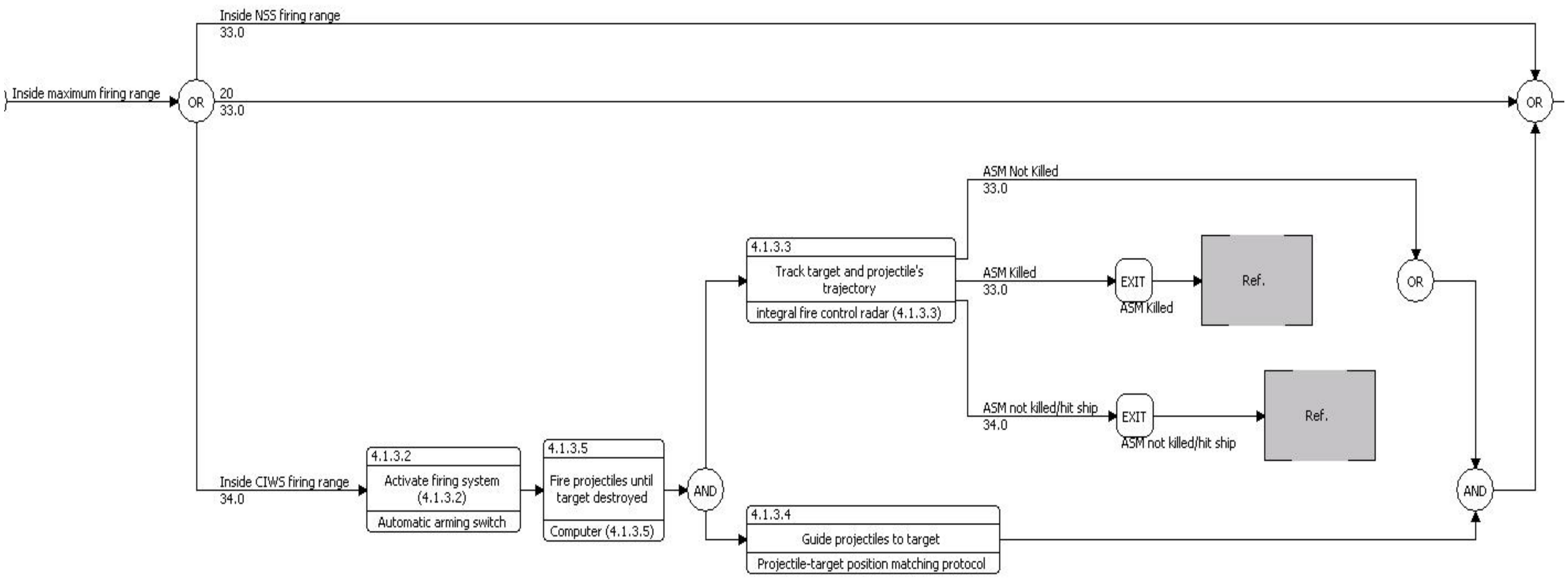

Figure 11. AAW EFFBD (ASM kill loop) Part 2

D. BEHAVIORAL MODEL VERIFICATION

Vitech's Modeling environment software, *CORE*, includes a feature called *COREsim*, which is a dynamic verification simulator. The defined system has fit into a behavioral model to show how the system is supposed to react in a specific scenario. To verify that the behavior expected is feasible, the model is run through simulations. *COREsim* provides automatic dynamic verification of the functional behavior model (Vitech Corporation, 2011).

Logic is verified to make sure that functions occur in the sequence they are supposed to. Doing this can identify inconsistencies as well as system limitations. For example, a time duration attribute can be assigned to each function block based on the estimated time needed for the respective allocated physical components to complete the tasks of the scenario. The scenario will dictate the time limit for the sum of the functions to complete the tasks. As time is the ratio of speed to distance, the time limit for an AAW scenario is determined by the velocity and initial range of the incoming ASM.

COREsim generates a timeline for each simulation that displays when functions are begun, how long they wait for a trigger, the time it takes to perform, and which branches were used. For demonstration purposes, arbitrary probabilities were assigned to each of the branches so that all of the function threads could be simulated.

Probabilities were used to assign branch determination logic based on the range of the incoming ASM and the range limitations of the four surface-to-air weapon systems on the ship. The simulation clock begins when the missile is at the assumed initial detection range, assumed to be a distance of 185 km. In reality, detection range of the air search radar system is determined by a plethora of variables, which can be characterized by a probability distribution function specific to the type of radar system and the missile threat. However, for concept demonstration in this two dimensional AAW scenario, a single estimated value was used for the input parameters that effect the function durations and branch selection logic. Those parameters are listed in Table 5 (Drennan, 1994) and (Integrated Publishing, 2007).

Table 5. Fixed System Parameters

System	Parameter	Value	Units
Air Search Radar			
	Detection Range	185	Km
	Processing Time	1	Seconds
ASM			
	Velocity	0.3	Km/sec
Surface to Air Weapon System			
	SM Velocity	1	Km/sec
	VLS Activation time	2	Seconds
	Maximum Engagement Range	160	Km
	Minimum Engagement Range	4.5	Km
Long-Range Surface-to-Air Weapon System			
	NSSM Velocity	0.44	Km/sec
	NSSM Activation time	2	Seconds
	Maximum Engagement Range	30	Km
	Minimum Engagement Range	0.8	Km
Medium-Range Surface-to-Air Weapon System			
	RAM Velocity	0.68	Km/sec
	RAM System Activation time	2	Seconds
	Maximum Engagement Range	8	Km
	Minimum Engagement Range	0.8	Km
Short-Range Weapon System			
	Burst Length	4	Seconds
	Muzzle Velocity	1	Km/sec
	CIWS Activation Time	1	Seconds
	Maximum Engagement Range	1.5	Km
	Minimum Engagement Range	0	Km

For the purposes of verification of the behavioral model, durations will be assigned to the function blocks based on the first launch opportunity for each weapon system. Figure 12 shows how the range of the incoming missile changes with time, the first opportunity for launch given a maximum intercept range of 160 km, and the time of impact given the SM hits the ASM. Figure 13 shows the same things, but illustrates how a SM slower velocity and reduced maximum engagement range changes the time of the first launch opportunity and the time of impact. These estimated values were incorporated in the function durations, for the assumed single launch.

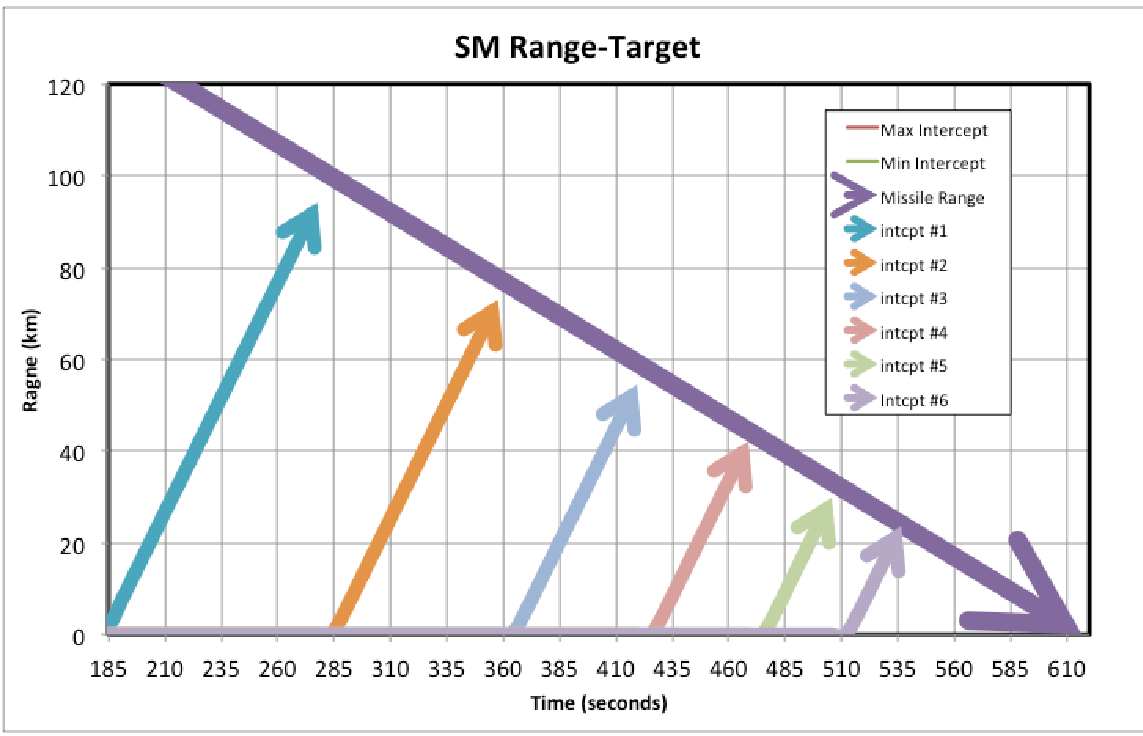

Figure 12. SM Range Target Graph

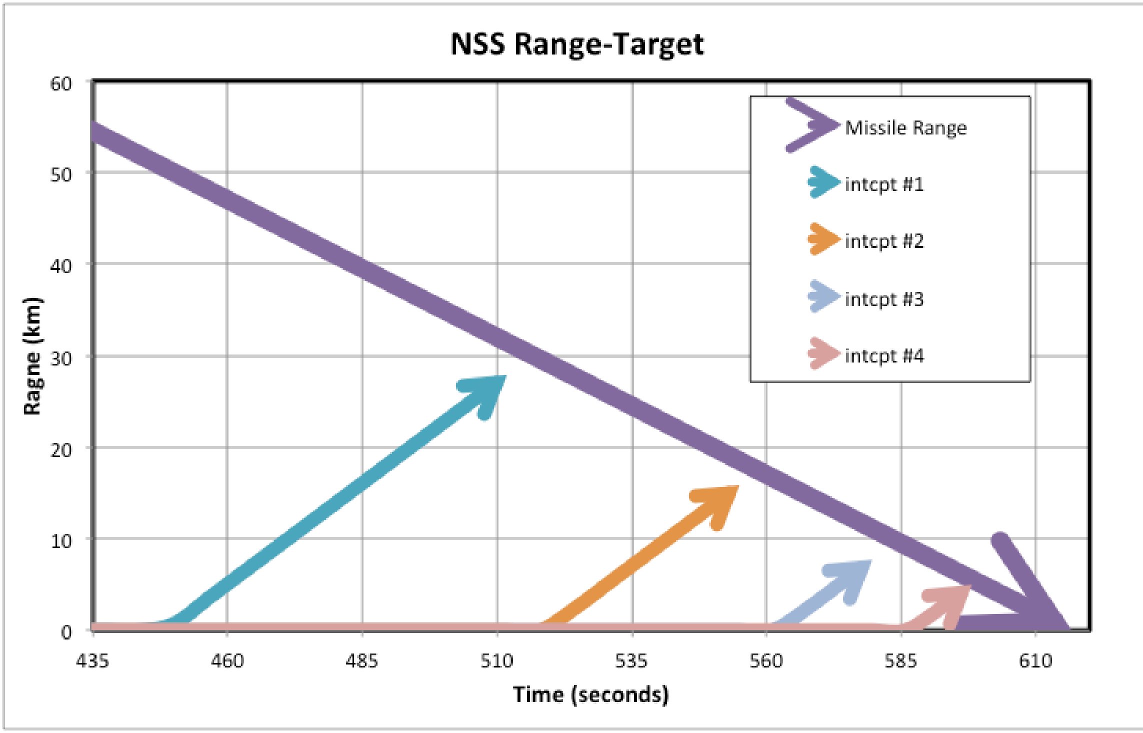

Figure 13. NSSM Range Target Graph

Table 6 shows the resulting time durations that were calculated for each function block included in the AAW EFFBD. The time to launch missiles of the four SAM systems (SM, NSSM, RAM, and CIWS) includes the time that it takes the ASM to travel within engagement range and the time for the SAM to travel from the ship to the intercept point.

Table 6. Function Block Durations

Number	Name	Duration
3.1.3	Detect airborne targets	1
3.2.1	Classify surface and airborne targets electronically	1
3.3.4.2	Activate launching system (SM)	2
3.3.4.3	Launch missiles	180
3.3.4.5	Guide missile to target	100
3.5.4.4	Track missile's flight path	100
4.1.1.2	Activate launching system (NSSM)	2
4.1.1.3	Launch missiles	450
4.1.1.4	Track missile's flight path	70
4.1.1.5	Guide missile to target	70
4.1.2.2	Activate launching system (RAM)	2
4.1.2.3	Launch missiles	580
4.1.2.4	Guide missile to target	12
4.1.2.5	Track missile's flight path	12
4.1.3.2	Activate firing system (CIWS)	1
4.1.3.3	Track target and projectile's trajectory	6
4.1.3.4	Guide projectiles to target	4
4.1.3.5	Fire projectiles until target destroyed	605

With all the time durations set, the EFFBD can be simulated. The result of the simulation is a graphical display of how the allotted resource (e.g., time) was used up in reference to the maximum time of the scenario. Clearly, in this simulation, as well as for a real world situation, the scenario has a variety of different outcomes Figure 14 and Figure 15 are only two examples of how the scenario could have gone.

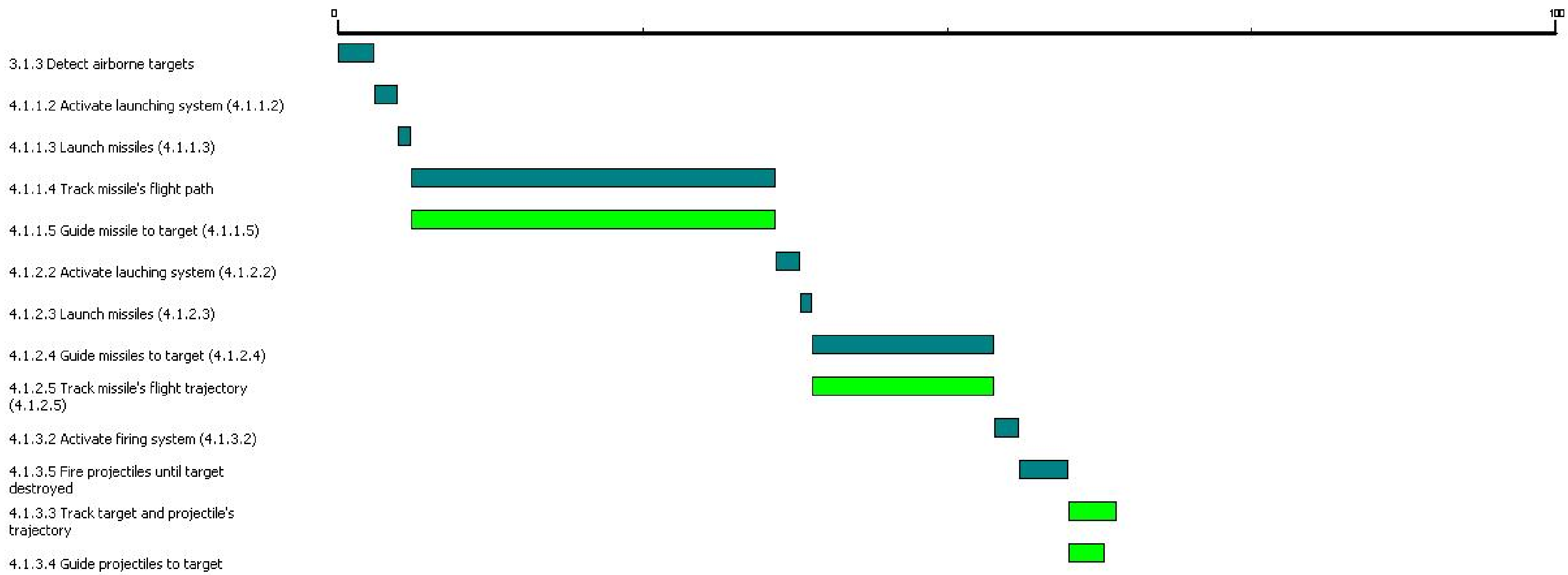

Figure 14. AAW EFFBD Verification Simulation Result (1)

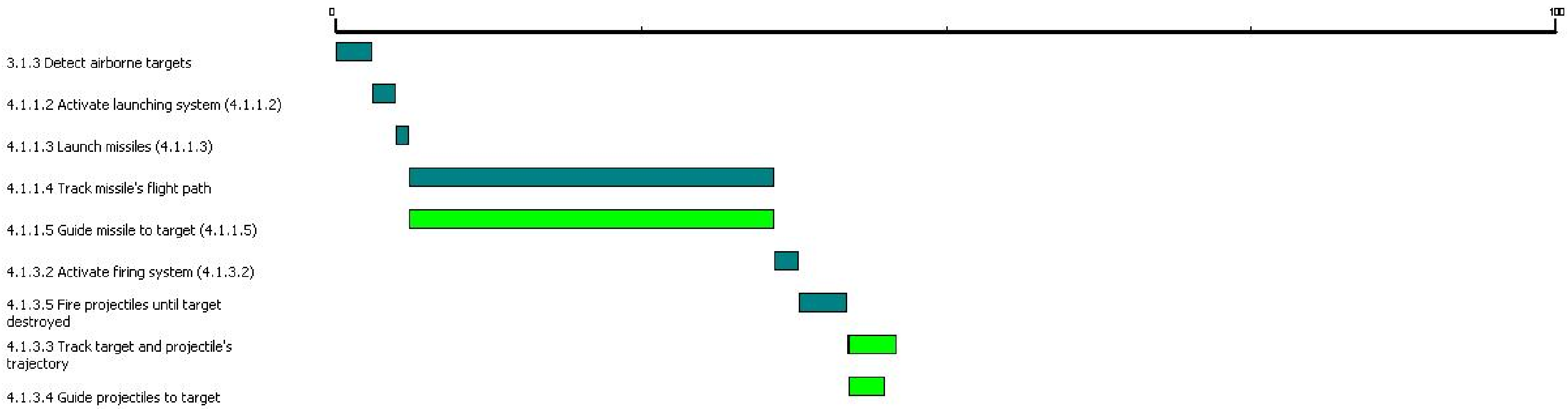

Figure 15. AAW EFFBD Verification Simulation Result (2)

In Figure 14, an incoming ASM was detected; the system launched an NSSM missile, which failed to destroy the ASM. Then the ASM was determined to be within medium range weapon distance so a RAM was launched, which also failed. Upon sensing the RAM failure, in the final seconds of the scenario, once the incoming ASM was within CIWS firing range, it was engaged and destroyed by CIWS.

The outcome in Figure 15 shows that the ASM was detected and determined to be within firing range for the NSSM. One NSSM was fired and failed. The system looped back to where the weapon system is determined based on the range of the ASM. As it was within firing range for the short-range surface to air weapon system, it was engaged and destroyed by CIWS.

In both simulations, the functions were completed within the allotted scenario time limit, meaning the missile was destroyed before it impacted the ship. This verifies that the example systems (NSSM, CIWS, RAM) with their approximated characteristics can complete this scenario within a satisfactory amount of time.

Although AAW is the only mission modeled for behavior in this thesis, this method of behavioral modeling and verification can be performed for each mission area of a ship. Other resources can be assigned besides time such as power and ammunition to demonstrate functional and physical inconsistencies and limitations in this very early stage of the design process.

Once it is determined how the system will perform in an AAW scenario against a single inbound enemy plane with one ASM, it can be modeled with more detail in a DES model. That will help determine how individual system characteristics impact the overall ship performance. In the next section, an AAW scenario will be simulated in a DES model, and the air search radar system characteristics will be varied to determine how radar detection range effects ship performance.

E. CHAPTER SUMMARY

This chapter demonstrated the architecture development step of the ship design method. The requirements captured in the DRM were allocated to functions, which were decomposed by sub-functions and mapped to physical components. A behavioral model was created to determine and illustrate how this architecture acts in a mission scenario. Then the logic of the behavioral model was verified by the use of a simulation that monitors resource use. This architecture and behavioral model will be the basis for development of a mission effectiveness model in the next section.

IV. MISSION EFFECTIVENESS

The purpose of the previous section was to demonstrate the development of a system description. The system described in this thesis is a surface combatant with a list of functions and a list of general physical components that will enable it to operate independently in shallow water and defend itself from an ASM attack. The description also includes a behavioral model, which shows how the system acts in a specific scenario, AAW in this case. This section will take the description of what the system is and how it acts in a scenario and determine how the characteristics of the individual subsystems impact the overall performance. For demonstration, the air search radar detection range will be varied to determine how it affects the scenario outcome.

Effectiveness is measured in terms of achievement of mission objectives and desired results. The sum of individual MOPs specific to the threat scenario quantifies the MOE. For this thesis, the MOE used for demonstration of concept is the capability to perform AAW. The probability of kill is recognized as the product of vulnerability and susceptibility, neither of which is being directly accounted for in this simple example effectiveness model. The primary MOP is the inverse of the probability of taking a hit ($1-P_{Hit}$), which in, this study, will be referred to as the probability of survival, (P_s). P_s will be assessed in a DES Model.

A. ANTI-AIR WARFARE MODEL

This thesis continues previous work by Welch (2011) about investigating the link between combat system capability and ship design characteristics using MBSE. The *Extendsim* model of that work matches the OPSIT of this thesis in that it generates a single threat and the system can react with multiple surface-to-air weapons. Furthermore, this existing effectiveness model will be used because it has the capability to vary one input parameter, air search radar detection range.

The following statements describe specific boundaries of the DES model:

- The model is based on only one mission area (point defense in AAW).

- The model only evaluates P_s of the ship.
- The model is focusing only on the aircraft's standard ASM and the ship's standard SAM for its defensive capabilities and does not consider the other weapon systems or countermeasures.

To make the model straightforward and simple for the purposes of demonstration, many assumptions have been incorporated into the development of the logic. The following list makes up the major assumptions used to simplify the model:

- The ship is stationary.
- The ship is at its highest level of combat readiness; I&W that an air attack is imminent, all watch standers are alert, and approval for defensive actions has been issued.
- The ship utilizes a shoot-look-shoot doctrine.
- The enemy aircraft's tactics consist of shooting exactly 1 ASM when it reaches its firing range, and immediately retreating from the area.
- If the ship or aircraft is hit, $P_S = 0$.
- The $P_{Detection}$ of both the ship and aircraft's radar is equal to 1.
- All environmental and time factors (weather, sea state, visibility, temperature, etc.) are ideal for ship and aircraft combat system and weapon performance.

1. Model Logic

Each simulation begins with the generation of one enemy target, which will be identified as either an ASM or an aircraft. In the case of an aircraft, the system will perform a series of queries and decisions before it engages the target. Figure 16 shows the logic flow of the *Extendsim* effectiveness model.

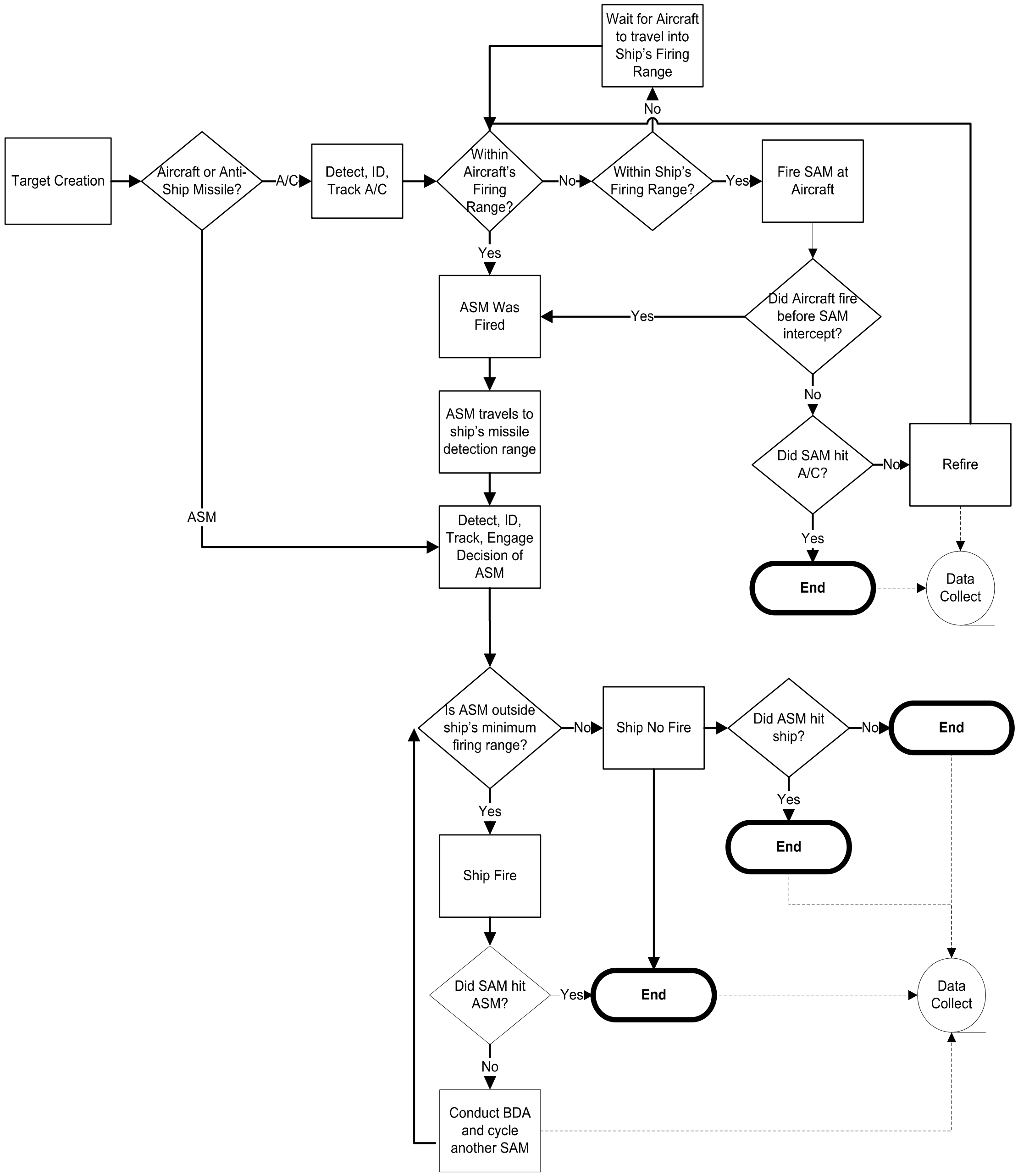

Figure 16. Logic Diagram for Warfare Effectiveness Model (From Welch, 2011)

2. Input Parameters

The AAW model incorporates several inputs, most of which will remain constant to keep the model simple. Table 7 includes all of the input parameters that will not change.

Table 7. Parameters Values Used in Effectiveness Model

Constant Parameter	Value
Maximum Aircraft Firing Range	100 km
Maximum Ship Firing Range	150 km
Minimum Ship Firing Range	2 km
Aircraft Velocity	0.3087 km/s
SAM Velocity	0.8575 km/s
ASM Velocity	0.686 km/s
SAM P_k of Aircraft	0.65
SAM P_k of ASM	0.6
ASM P_k of Ship	0.85

3. Variable Input Parameters

One input parameter was chosen to be variable to demonstrate how the model, and therefore the system, might react with a different physical component. For this thesis, the chosen variable is the radar detection range. This input parameter is representative of the capability of the air search radar. Each air search radar system has different corresponding characteristics including weight, power usage, volume, and height. The primary capability that the air search radar contributes to the AAW scenario is the initial effective detection range, which is a function of each of these characteristics.

Appendix E contains screen shots of the entire *ExtendSim* model.

B. EFFECTIVENESS MODEL RESULTS

The MOP, P_s, was determined for each radar detection range from 20 km to 300 km in 20 km increments. Each range was simulated 1000 times to achieve a high confidence in the mean of the P_s. Figure 17 shows the resulting means of the probability of survival versus the simulated detection range.

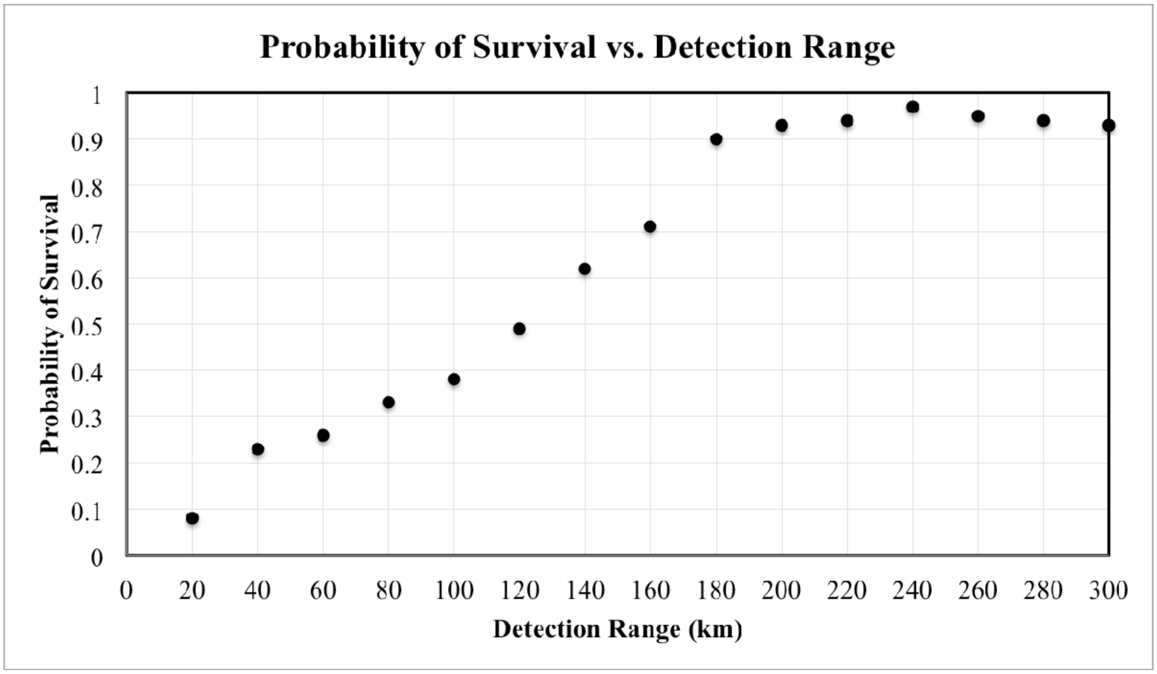

Figure 17. Probability of Survival vs. Detection Range Graph

Approximately 180 km is the point at which any additional range of the radar's detection adds little to no increase in the system's probability of survival. Therefore, if the stakeholders would like to have their system perform at a level of 40%, 90%, or 98%, the designers would select radar systems that can operate with 100km, 180km, and 240km, respectively.

C. CHAPTER SUMMARY

The system architecture, functional and physical, was used to create a warfare effectiveness model. The DES model determined how a characteristic of an individual system on the ship (air search radar detection range) impacts the MOP. This determination will help decision makers and designers create a ship that meets the needs and requirements stated for this project in the DRM.

V. SHIP SYNTHESIS

Now that a functional and physical architecture has been developed for a design solution and the effectiveness of that solution has been determined, alternative ship designs can be created. This thesis intends to make a design space rather than a single design solution. The design space reveals the tradeoffs that the solution experienced given a change in capability. To achieve this end, an *Excel*-based ship synthesis model is used to create three alternative designs each with different corresponding capabilities. The capability of the ship is represented by the MOE in the effectiveness model.

Three design alternatives are created to demonstrate a design space and the tradeoffs between cost and capabilities. The three alternatives ship designs will incorporate radar systems that achieve the following probabilities of survival in the AAW scenario simulated in the previous section: 40%, 90% and 99%.

A. EXCEL MODEL

The ship synthesis model used to derive the design alternatives is a Microsoft *Excel* Spreadsheet created by Dr. Clifford Whitcomb based on an original ship synthesis model developed through the Naval Construction and Engineering Program at MIT. It was created with the capability to receive inputs from the user based on a reference platform and be manipulated with manual iteration to output a stable and balanced ship design. The design calculations within the model are based upon those used in the ship synthesis program used by the Navy. Cost estimations, also included in the synthesis model, are very simple and based on the displacement of the ship.

B. INPUT PARAMETERS

As an iterative process, the synthesis model needs to have a starting place on which to base the initial calculations. All inputs are selected to reflect the requirements stated in the DRM. The combat system suite that will meet or exceed the capabilities requirements is chosen based on the options built into the spreadsheet model.

1. Reference Platform

The synthesis model in the right general direction it needs to have an existing platform design on which to start iterations. The NATO Specialist Team on Small Ship Design published a study, “Paper on Small Ship Design,” (2004), which analyzed two kinds of small ship, Offshore Patrol Vessel (OPV) and Small Littoral Combatant (SLC). Both platforms can be extremely useful in supporting or conducting Power Projection missions, especially with respect to littoral operations, which fits nicely into the mission profile of this thesis. The missions and operations of the two platforms are similar in some areas but differentiated by their warfare capabilities, AAW in particular.

The OPV is intended for this purpose of patrolling the waters of an exclusive economic zone and specializes in conducting law enforcement operations. The SLC is better suited for Naval operations. Naval operations, as described in the NATO publication, are Military Aid, Military Patrol, Military Control, and Military Power. It is Military Power and Control that include the defensive AAW capability that is required for the mission profile of this thesis. Since the DRM for this thesis requires that the ship have some AAW capability, the author selected the SLC as the most appropriate reference platform for design synthesis. Some characteristics of the SLC from the NATO design paper are listed in Figure 18. Many of these values were used as the starting point of iteration for the ship alternatives created for this thesis.

```
2000 LITTORAL COMBATANT

CHARACTERISTICS
---------------
LENGTH (LOA)                328.00 FEET        99.97 METERS
LENGTH (LBP)                308.00 FEET        93.88 METERS
BEAM (B)                     43.42 FEET        13.23 METERS
DRAFT, FULL LOAD (T)         12.39 FEET         3.78 METERS
MEAN HULL DEPTH              29.76 FEET         9.07 METERS
FREEBOARD AT FP              20.11 FEET         6.13 METERS
FREEBOARD AT AP              17.11 FEET         5.22 METERS
PRISMATIC COEFFICIENT          .6200     CWP     .7840
MAXIMUM SECTION AREA COEF.    .7985     CIT     .0527400
BLOCK COEFFICIENT              .4951     COMPLEMENT  110.
DISPLACEMENT: MOLDED      2342.73 L.T.      2380.32 METRIC TONS
              APPENDAGE     35.14 L.T.        35.70 METRIC TONS
              DOME          48.50 L.T.        49.28 METRIC TONS
              FULL LOAD   2426.37 L.T.      2465.31 METRIC TONS
CUBIC NUMBER/100000          4.169              .1181
TOTAL ENCLOSED VOLUME   408780.60 CU.FT.   11575.38 CUBIC METERS

BODY PLAN:       30 KN CUTTER
GERTLER WORM:        HIGH SPEED FRIGATE
PCOEF (=EHP/SHP):    HIGH SPEED FRIGATE
BOW DOME:  YES

                    FULL LOAD   MEAN TRIAL     MIN. OP.
DRAFT, FEET             12.39        11.96        11.82
DISPL, LONG TONS      2426.37      2292.80      2250.39
DISPL/(.01*LBP)**3      83.0434      78.4718      77.0202
GM/BEAM                   .0871        .0819        .0850
TRIAL SPEED, KNOTS      31.24        31.94
SUSTAINED SPEED, KNOTS  29.16        29.73

TRIPLE SCREW CODOG PROPULSION PLANT (OUTBOARD CPP PROPS, DIA=10.76 FT., RPM= 1600
CENTERLINE CPP PROP, DIA=14.2 FT.,RPM=210.00)
     TWO HIGH SPEED DIESELS   8325.00 HP EACH OUTBOARD P/S
     31000.00 HP GAS TURBINE CENTERLINE

ENDURANCE (OPERATING PROFILE):
  STORES & PROVISIONS = 20.00 DAYS
  SPEED    FULL LOAD        MEAN TRIAL LOAD    FUEL OIL
  KNOTS  DIST. NM    DAYS  DIST. NM    DAYS    LONG TONS
  16.00   4367.42   11.37   4499.25   11.72      278.73

ENCLOSED DECK AREA (SQFT.):
     AVAILABLE =  30417.89     REQUIRED =  30111.44
     AVAILABLE LESS REQUIRED =    306.46

OPEN WEATHER DECK AREAS:
     1668.78 SQFT. FWD OF STATION  3.247
     3275.97 SQFT. AFT OF STATION 15.390
```

Figure 18. 2000-Tonne SLC Synthesis Model Output (From NATO Naval Group 6 Specialist Team on Small Ship Design, 2004)

There are some things to point out about this reference ship design that are not necessarily desirable in the ship alternatives to be created in this thesis. For example, the number of propellers. Three propellers leads to very complicated shafting arrangements and complicated the aft section design.

2. Initialization

Once the initial characteristics of the reference platform are considered, the *Excel* model can be populated and adjusted based on system requirements and design considerations. Table 8 includes all of the input variables used for the three design alternatives.

Table 8. Input Values for Ship Synthesis Model

Description	Variable	Value	Units
Gross Characteristics			
Initial Full Load Displacement	W_{FL1}	2426	lton
Initial Payload Fraction	F_P	0.1	
Prismatic Coefficient	C_P	0.6	
Midship Section Coefficient	C_X	0.875	
Beam to Draft Ratio	C_{BT}	3.5	
Displacement Length Quotient	$C_{Disp\text{-}L}$	64	Lton/ft^3
Average Deck Height	H_{DK}	9	ft
Depth at Station 10	DSTA10	31	feet
Energy			
Payload Cruise Elect Power Req't	kW_{PAY}	623.49	kW
Sustained Speed Requirement	V_S	30	knt
Endurance Speed Requirement	V_E	16	knt
Range Requirement	E	8000	knt x hr
Machinery			
Number of Propellers	N_P	2	
Number of APUs	N_{APU}	0	
Number of Propulsion Engines	N_{PENG}	3	
Number of Ship Service Generators	N_G	5	
Fuel System	FS	NONCOMP	
Space			
Deckhouse Area, C&D	ADPC	4116	ft2
Deckhouse Area, Armament	ADPA	5258	ft2
Hull Area, C&D	AHPC	5787	ft2

Description	Variable	Value	Units
Hull Area, Armament	AHPA	3784	ft2
Area, Sonar Dome	ASD	215	ft2
Weight			
Structure			
Armor	Wt164	23	lton
Sonar Dome Structure	Wt165	0	lton
Hull Material	HM	HTS	
Deckhouse Material	DM	Steel	
Hull Material Coefficient	CHMAT	0.93	
Deckhouse Material Coefficient	CDHMAT	2	
CPS Type	CPS	Full	
Payload			
Payload Weight	W_P	571.51	lton
Payload VCG	VCG_P	24.24	ft
Variable Payload Weight	W_{VP}	199.47	lton
Variable Payload VCG	VCGVP	25.44	ft
Stores Period	TS	30	days
Command and Surveillance (W400 less 420 and 430)	WP400	215.93	lton
Mission Handling/Support (W500)	WP500	39.46	lton
Mission Outfit (W600)	WP600	7.74	lton
Armament (W700)	WT7	93.65	lton
Ordinance (WF20)	WF20	135.67	lton
Number Helicopters	NHELO	0	
Helo Weight (WF23)	WF23	0	lton
Helo Fuel (WF42)	WF42	63.8	lton
Sonar Dome Water	WT498	0	lton
Sonar Dome Water VCG	VCG498	0	ft
Desired Radar Detection Range	R_D	100	km
Manning			
Officers	N_O	15	people
Enlisted (including CPO)	N_E	95	people
Total	N_T	110	people
SCN Cost Constraint	SCN	700	M$

Some values have been adjusted from the reference model variables in order to meet the requirements of a balanced ship. The power requirements of the ship with the selected combat system require more than four ship service diesel generators (SSDG) in

order to support the estimated electrical load for a cruising state. This is because the Navy requires that all naval ships have one SSDG on standby in case one of the operating SSDGs fails.

Stores requirements was increased from the reference SLC duration of 20 days to 30 days in order to support the mission profile that involves the ship being positioned in the Yellow Sea off the coast of the adversary. The area is remote, fog is an ever-present issue for vertical replenishment by helicopter, and very shallow for larger replenishment ships. In order for commanding officers to have confidence in this ship being able to support this mission for a useful period of time, it should have the ability to carry enough stores and provisions for 30 days.

Inputs that were not available in the reference platform design characteristics were selected to support standard naval practices. The number of people on the ship was designated by the characteristics of the reference ship, however the spreadsheets accounts for officers and enlisted personnel differently with respects to space and weight. The 110 people were separated into 15 officers and 95 enlisted personnel to support the calculations in the spreadsheet.

The electrical power generators used in this model are DDA149TI Diesel generators, which can operate at 1000kW vice the 880kW generators of the SLC reference ship.

3. Combat Systems Configuration

Requirements that impact the combat systems of the alternative ship designs are primarily those that are relevant to AAW and sustained independent operations. Air and surface search radar systems, navigation, communications, surface to air weapon systems, and countermeasures are the primary systems that are necessary to support these operations. The combat system suite of the reference ship is very similar to one of the suite options in the *Excel* model.

Three combat system suites from the *Excel* model are available based on complexity. The first option contains a very broad variety of systems that would support

independent operations in a large number of missions. The second option is equipped to support a handful of primary warfare areas independently and others as a support platform in a battle group. The third combat systems suite has the non-advanced version of weapon and sensor system.

The combat systems suite selected for incorporation into the three design alternatives is the second option. The DRM of this thesis requires that the ship have AAW capabilities. This suite has an air search radar system, a vertical launch system, a combat information center (CIC) with a command and control computer system and two large screen displays, an advanced long range cruise missile weapon control system, and a Evolved Sea Sparrow Missile (ESSM) launcher system to support AAW.

Table 9 provides a list of the major combat systems, based on the second option, and the corresponding weight, vertical center of gravity, area, and power usage in a normal “cruise” state as well as a fully ready “battle” configuration.

Table 9. Combat Systems Payload Data

PAYLOAD NAME	***WT KEY***	***WT***	***VCG DATUM***	***VCG FT AD***	***AREA KEY***	***HULL FT2***	***DKHS FT2***	***CRUISE KW***	***BATTLE KW***	***WT MOMENT***
STEEL LANDING PAD [ON HULL] - HELICOPTER CAPABLE	W111	10.7	30	0.20	NONE	0	0	0	0	323.14
32 CELL VLS ARMOR	W164	14	38.31	-10	NONE	0	0	0	0	396.42
GUN ARMOR	W164	9	37.8	-8.00	NONE	0	0	0	0	263.7
5M BOW SONAR DOME W/MINE AVOIDANCE	W165	85.7	0	-1.5		0	0	0	0	-128.55
GROUP 100	**WP100**	119.4				0	0	0	0	
CIC W/ COMMAND AND CONTROL COMPUTER SYSTEM & 2X LARGE SCREEN DISPLAYS	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03	688.11
NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5	473.85
ADV DIGITAL C4I (JTIDS, LINK 16/LINK 22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67	157.71
MULITIFUNCTION SURFACE SEARCH RADAR	W456	40	51	-10.00	A1121	0	70	8	0	1640
AIR SEARCH RADAR	W452	2.89	51	-7.1	A1121	0	553	15.3	30.77	126.8
IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4	106.72
X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16	464.43
5M BOW SONAR DOME ELEX W/MINE AVOIDANCE	W457	57.7	0	9.3	A1122	1942	0	0	0	536.61
BATHYTHERMOGRAPH	W458	0.31	30	-10.90	A1122	85.5	0	0	0	5.92
SONOBUOY PROCESSING SYSTEM	W459	5.26	51	-44.86	NONE	0	0	1.15	1.15	32.30

PAYLOAD NAME	***WT KEY***	***WT***	***VCG DATUM***	***VCG FT AD***	***AREA KEY***	***HULL FT2***	***DKHS FT2***	***CRUISE KW***	***BATTLE KW***	***WT MOMENT***
ELECTRONIC WARFARE SYSTEM W/ ACTIVE ECM	W460	4.4	33.4	20.60	NONE	0	0	6.4	6.4	237.6
ELECTRO-ACOUSTIC DECOY (NIXIE)	W461	0.24	30	-6.20	A1142	200	0	3	4.2	5.71
DECOY LAUNCHING SYSTEM W/6 LAUNCHERS	W462	0.96	33.4	5.39	NONE	0	0	2.4	2.4	37.23
5"/54 GUN FIRE CONTROL SYSTEM	W463	7.50	51	-4.00	A1212	0	168	6	15.4	352.5
MISSILE FIRE CONTROL SYSTEM - STIR/CORT/IADT/CEC	W464	6.29	51	-1.40	NONE	0	0	50.3	85.8	311.98
VLS WEAPON CONTROL SYSTEM	W465	0.7	35.0585	2.54	A1220	56	310	13.62	19.69	26.318
ADVANCED LONG RANGE CRUISE MISSILE WEAPON CONTROL SYSTEM	W466	5.6	33.4	-7.80	NONE	0	0	13.27	13.27	143.36
ASW CONTROL SYSTEM [ASWCS] W/SSTD	W467	3.75	33.4	-12.60	A1240	320	0	8.61	8.61	78
COMBAT DF	W468	8.26	33.4	21.00	A1141	0	448	15.47	19.34	449.34
ELECTRONIC TEST & CHECKOUT	W469	1.1	38.315	10.80	NONE	0	0	0	0	54.02
GROUP 400	**WP400**	215.92				5787.1	4115.7	503.66	569.39	
32-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	3.5	35.05	-0.46	NONE	0	0	0	0	121.09
AVIATION FUEL SYS	W542	4.86	35.05	-11.00	A1380	30	0	2	2.9	116.92
RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4	1040.55
GROUP 500	**WP500**	39.46				249	33	6.4	7.3	
5M BOW SONAR DOME HULL	W636	6.7	0	-2.5	NONE	0	0	0	0	-16.75

PAYLOAD NAME	WT KEY	WT	VCG DATUM	VCG FT AD	AREA KEY	HULL FT2	DKHS FT2	CRUISE KW	BATTLE KW	WT MOMENT
DAMPING										
AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1360	194	75	0	0	31.78
GROUP 600	**WP600**	7.74				194	75	0	0	
1X GUN	W710	30	38.8	-6.20	A1210	270	0	36.18	37.88	933
2X SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.6	141.73
VLS 32-CELL	W721	54	35.0585	1.14	A1220	128	0	69.65	69.65	1954.71
2X SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5	197.58
GROUP 700	**W7**	93.65				398	368	107.83	114.13	
GUN AMMO - 600 RDS	WF21	20	37.3	-28.40	A1210	798	68	0	0	178
LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	72	35.0585	0.34	A1220	1420	720	0	0	2548.69
SSM (OVER THE HORIZON) MISSILES -- 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0	145.15
ASW TORPEDOES -- 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0	48.82
DECOY LAUNCHING SYS SRBOC CANNISTERS - 100 RDS	WF21	2.2	33.4	11.60	NONE	0	0	0	0	99
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.1	33.4	-6	NONE	0	0	0	0	112.34
HELO 18 X TORPEDOS & SONOBUOYS & PYRO	WF22	9.87	35.05	4.80	A1374	0	588	0	0	393.40
2X HELOS AND HANGAR (BASED)	WF23	12.73	35.05	4.50	A1340	0	3406	5.6	5.6	503.57
AVIATION SUPPORT AND SPARES	WF26	9.42	35.05	5.00	A1390	357	0	0	0	377.35

PAYLOAD NAME	***WT KEY***	***WT***	***VCG DATUM***	***VCG FT AD***	***AREA KEY***	***HULL FT2***	***DKHS FT2***	***CRUISE KW***	***BATTLE KW***	***WT MOMENT***
BATHYTHERMOGRAPH PROBES	WF29	0.21	30	-6.00	NONE	0	0	0	0	5.04
GROUP WF20	**WF20**	135.67				2943	4782	5.6	5.6	
LAMPS MKIII: AVIATION FUEL [JP-5]	**WF42**	63.8	0	10.4	A1380	0	0	0	0	663.52
VARIABLE MILITARY PAYLOAD (WF20+WF42)	**WVP**	199.47								
ARMAMENT (WP500, WP600, W7, WF20)						3784	5258			
								KWP		
TOTAL PAYLOAD	***WP***	675.64				9571.1	9373.7	623.49	696.425	16378.82

C. BALANCING A SHIP

The spreadsheet is set up with check and balance display to iterate through the model by changing certain values until a satisfactory balanced design is reached. Table 10 lists the areas of design and the criteria they must meet, all of which are unique to a single iteration. These design areas are gross characteristics, energy, space (in terms of volume and area), weight, stability, and cost.

For the iteration captured in Table 10, the depth at station 10 has a required minimum value of 27.69ft. The table shows that the achieved value for the design alternative must be greater than this value in order to have stability given the other characteristics of the design such as length, beam, and weight. Energy per online generator required by the estimated payload including the combat system suite is 929.74kW for this iteration, which must be less than the available installed generator capacity of 1000kW, which is the rating of the DDA149TI Diesel generators used in the model.

Table 10. Balanced Ship Evaluation

Description	Achieved Variable	Value	Units		Required Variable	Value	Units
Gross Characteristics							
Length on Waterline		415.3					
Beam		50.8					
Draft		14.5					
Depth at Station 10	DSTA10	31	ft	>	D10MIN	27.69	ft
Energy							
Sustained Speed	V_S	30	knt			30	knt
Endurance Speed	V_E	16	knt			16	knt
Installed Shaft Horsepower	DHP	49470	hp	>	PIREQ	40098.42	hp
Installed Generator Capacity	kWG	1000	kW	>	kWGREQ	929.74	kW
Space							
<u>Volume</u>							
Deckhouse Volume	VD	175000	ft3		VDR	127688	ft3
Arrangeable Hull Volume	VHA	272529	ft3		VHR	305081	ft3
Total Arrangeable Volume	VTA	447529	ft3	>	VTR	432769.30	ft3
<u>Area</u>							
Arrangeable Hull Area	AHA	30281	ft2		AHR	33898	ft2
Arrangeable Deckhouse Area	ADA	19444	ft2		ADR	14188	ft2
Total Arrangeable Area	ATA	49725	ft2	>	ATR	48085.47	ft2
Weight							
Full Load Weight	WFL	4585.0			WT	4584.7	lton
Stability	CGMB	0.11447		>	CGMBR	0.1	
Cost	SCN	700	M$	>	TLSAC	646.40	M$

D. COST ESTIMATION

Various cost variables are calculated to demonstrate, in relative terms, the significance of the design considerations, including capabilities and ship characteristics. The synthesis model includes simplified cost models for the lead ship cost, follow ship cost, and life cycle cost. The majority of the cost figures within each model are based on weight. Scaling factors derived from historical data are applied to the calculated characteristics of the design alternatives to get an estimated cost value for each part of the ship or Ship Work Breakdown Structure (SWBS) group.

Table 11 shows the lead ship cost calculations spreadsheet for the first alternative with scaling factors, shown in red text.

Table 11. Lead Ship Cost Data

Description	Variable	Value	Units
Additional Characteristics			
Ship Service Life	LS	30	years
Initial Operational Capability	YIOC	2010	year
Total Ship Acquisition	NS	20	ships
Production Rate	RP	3	ships/year
Inflation			
Base Year	YB	1999	
Average Inflation Rate	RI	**3.73**	
Inflation Factor	FI	1.93	
Lead Ship Cost - Shipbuilder Portion			
SWBS Costs:			
Structure	KN1	**0.55**	
	CL1D	9.84	M$
Propulsion	KN2	**1.20**	
	CL2D	27.47	M$
Electric	KN3	**1.00**	
	CL3D	18.90	M$
Command, Control, Surveillance (less payload GFM cost)	KN4	**2.00**	
	CL4D	13.39	M$

Description	Variable	Value	Units
Auxiliary	KN5	**1.50**	
	CL5D	41.28	M$
Outfit	KN6	**1.00**	
	CL6D	17.42	M$
Armament (less payload GFM cost)	KN7	**1.00**	
	CL7D	1.43	M$
Margin Cost	CLM	12.97	M$
Integration/Engineering (Lead ship includes detail design engineering costs for class)	KN8	**10.00**	
	CL8D	79.29	M$
Ship Assembly and Support (Lead ship includes all tooling, jigs, special facilites for class)	KN9	**2.00**	
	CL9D	17.34	M$
Total Lead Ship Construction Cost (BCC)	CLCC	239.32	M$
Profit Factor	FPROFIT	0.10	
Profit	CLP	23.93	M$
Lead Ship Price	PL	263.26	M$
Change Order Factor	COF	**0.12**	
Change Orders	CLCORD	31.59	M$
Total Shipbuilder Portion	CSB	294.85	M$
Lead Ship Cost - Government Portion			
Other Support Factor	OSF	**0.03**	
Other Support	CLOTH	6.58	M$
Program Manager's Growth Factor	PMGF	0.10	
Program Manager's Growth	CLPMG	26.33	M$
Weight of Costed Military Payload	WMP	471.03	lton
Combat System GFE CER	CSCER	**0.32**	M$/lton
Helo cost	HC	18.71	M$
Ordinance and Electrical GFE (Military Payload GFE)	CLMPG	289.69	M$
HM&E GFE Factor	HMEGFEF	**0.02**	
HM&E GFE (Boats, IC)	CLHMEG	5.27	M$
Outfitting Cost Factor	OCF	**0.04**	
Outfitting Cost	CLOUT	10.53	M$

Description	Variable	Value	Units
Total Government Cost	CLGOV	338.40	M$
Total End Cost	CLEND	633.24	M$
Total Lead Ship Acquisition Cost			
Post Delivery Cost (PSA) Factor	PSACF	**0.05**	
PSA Cost	PSAC	13.16	M$
Total Lead Ship Acquisition Cost	TLSAC	646.41	M$

Data for estimated follow ship cost and life cycle cost are provided in Appendix E.

E. SHIP ALTERNATIVES

In order to demonstrate a design space that shows the effects and significance of the variable AAW capability, synthesis, and cost estimation were conducted for three ships each with a different level of AAW capability. The first alternative performs rather poorly in the AAW scenario of the effectiveness model. The second and third alternatives both perform well and the cost of a small increment of increased capability will be revealed.

The capability being referred to in this section is the capability to perform AAW missions as determined in the effectiveness model. The approximate MOEs and corresponding detection ranges for each of the design alternatives are as follows:

- First alternative: 100km range for 40% Probability of survival
- Second Alternative: 180km range for 90% Probability of Survival
- Third Alternative: 240km range for 98% Probability of Survival

Analysis conducted by Welch (2011) revealed the correlation between air search radar systems performance (i.e., radar detection range) and weight and power usage. This correlation has been reduced down to two equations, which have been incorporated

into the ship synthesis model such that a single input parameter, radar detection range, will influence the total ship weight and cost.

1. First Alternative

The first alternative can be thought of as the baseline case with only 100km of radar detection range, which corresponds to approximately 40% probability of survival against an ASM threat. However, it comes out to have a total lead ship end cost of $633.24 million. The first alternative ship design, or the baseline design, has a total full load weight of 4584.7 long tons with only 12% made up of combat systems.

Table 12 provides a summary of the principal characteristics, weight, space, and manning for the first design alternative.

Table 12. First Alternative Design Summary

Principal Characteristics			Weight Summary		
			Description	Weight (lton)	
LWL	415.3	ft	Group 1	1427.6	
Beam	50.8	ft	Group 2	380.0	
Depth, Station 10	31.0	ft	Group 3	210.7	
Draft	14.5	ft	Group 4	273.4	
GMT	5.8	ft	Group 5	606.3	
GM/B Ratio	0.114		Group 6	317.0	
CP	0.6		Group 7	93.7	
CX	0.875		Sum 1 - 7	3270.9	
Sustained Speed	30.0	knt	Design Margin	330.9	
Endurance Speed	16.0	knt	Lightship Weight	3639.5	
Endurance	8000	nm	Loads	945.2	
			Full Load Weight	4584.7	
Number Main Engines	3		Full Load KG	18.77	ft
Main Engine Rating	17000	hp			
			Military Payload	571.5	lton
SHP/Shaft	25500	hp	Payload Fraction	0.12	
Propeller Type	CRP		Fuel Weight	692.7	lton
Propeller Diameter	14.6	ft			
			Manning Summary		
Number SSGTG	5		Officers	15	
SSGTG Rating	1000	kW	Enlisted (Including NCO)	95	
Maximum Margined Electrical Load	3347	kW	Total	110	
Area Summary			**Volume Summary**		
Hull Area	30281	ft2	Hull Volume	272529	ft3
Superstructure Area	19444	ft2	Superstructure Volume	175000	ft3
Total Area	49725	ft2	Total Volume	447529	ft3

The cost calculations for the first alternative are summarized in Table 13. This ship design, with the expectation that it will be in service for 30 years and have 20 ships in its class is estimated to cost a total of $32,880.52 million over the life of the program. With a learning rate factor of 0.94, the first follow ship is estimated to cost $500.99 million

Table 13. First Alternative Cost Information

Total End Cost	633.24	M$
Total Lead Ship Acquisition Cost	646.41	M$
Total Follow Ship Acquisition Cost	500.99	M$
Total Life Cycle Cost (Undiscounted)	32,880.52	M$

Tables 12 and 13 present the baseline values against which the second and third alternatives will be compared.

2. Second Alternative

This alternative has a much greater probability of survival against the ASM threat, however, that probability is not as good as the model will allow, which is 98%. The only change in input parameters was the value for radar detection range. With an increase of 80% in AAW performance (measured only by probability of survival) the total cost becomes $634.80 million and the total full load weight is 4587.4 long tons. This ship performs with a 90% probability of survival in the AAW scenario. The design summary for the second alternative is in Table 14.

Table 14. Second Alternative Design Summary

Principal Characteristics			Weight Summary		
			Description	Weight (lton)	
LWL	415.3	ft	Group 1	1428.3	
Beam	50.8	ft	Group 2	380.1	
Depth, Station 10	31.0	ft	Group 3	210.7	
Draft	14.5	ft	Group 4	275.7	
GMT	5.8	ft	Group 5	606.4	
GM/B Ratio	0.114		Group 6	317.0	
CP	0.6		Group 7	93.7	
CX	0.875		Sum 1 - 7	3274.1	
			Design Margin	331.2	
Sustained Speed	30.0	knt	Lightship Weight	3643.0	
Endurance Speed	16.0	knt	Loads	945.4	
Endurance	8000	nm	Full Load Weight	4588.4	
Number Main Engines	3		Full Load KG	18.78	ft
Main Engine Rating	17000	hp			
			Military Payload	573.7	lton
SHP/Shaft	25500	hp	Payload Fraction	0.13	
Propeller Type	CRP		Fuel Weight	692.9	lton
Propeller Diameter	14.6	ft			

			Manning Summary	
Number SSGTG	5		Officers	15
SSGTG Rating	1000	kW	Enlisted (Including NCO)	95
Maximum Margined Electrical Load	3348	kW	Total	110

Area Summary			Volume Summary		
Hull Area	30295	ft2	Hull Volume	272655	ft3
Superstructure Area	19444	ft2	Superstructure Volume	175000	ft3
Total Area	49739	ft2	Total Volume	447655	ft3

The estimated values for the second alternative are listed in Table 15. This shows that a ship that has a 90% probability of survival will have an estimated end cost of $634.84 million.

Table 15. Second Alternative Cost Information

Total End Cost	634.84	M$
Total Lead Ship Acquisition Cost	648.01	M$
Total Follow Ship Acquisition Cost	502.43	M$
Total Life Cycle Cost (Undiscounted)	32,928.33	M$

3. Third Alternative

The third ship is designed with a combat system that can perform at 98% probability of survival in the AAW effectiveness model. To create this alternative, the baseline design was modified for 240km detection range. Then the ship was evaluated and adjusted for balance and stability. Characteristics of the third alternative ship design are listed in Table 16.

Table 16. Third Alternative Design Summary

Principal Characteristics			Weight Summary		
			Description	Weight (lton)	
LWL	415.5	ft	Group 1	1428.9	
Beam	50.8	ft	Group 2	380.1	
Depth, Station 10	31.0	ft	Group 3	210.7	
Draft	14.5	ft	Group 4	277.4	
GMT	5.8	ft	Group 5	606.5	
GM/B Ratio	0.114		Group 6	317.1	
CP	0.6		Group 7	93.7	
CX	0.875		Sum 1 - 7	3276.6	
Sustained Speed	30.0	knt	Design Margin	331.4	
Endurance Speed	16.0	knt	Lightship Weight	3645.8	
Endurance	8000	nm	Loads	945.6	
			Full Load Weight	4591.4	
Number Main Engines	3		Full Load KG	18.79	ft
Main Engine Rating	17000	hp			
			Military Payload	575.3	lton
SHP/Shaft	25500	hp	Payload Fraction	0.13	
Propeller Type	CRP		Fuel Weight	693.1	lton
Propeller Diameter	14.6	ft			
			Manning Summary		
Number SSGTG	5		Officers	15	
SSGTG Rating	1000	kW	Enlisted (Including NCO)	95	
Maximum Margined Electrical Load	3349	kW	Total	110	
Area Summary			**Volume Summary**		
Hull Area	30309	ft2	Hull Volume	272780	ft3
Superstructure Area	19444	ft2	Superstructure Volume	175000	ft3
Total Area	49753	ft2	Total Volume	447780	ft3

Cost data for the third alternative is included in Table 17.

Table 17. Third Alternative Cost Information

Total End Cost	636.04 M$
Total Lead Ship Acquisition Cost	649.22 M$
Total Follow Ship Acquisition Cost	503.51 M$
Total Life Cycle Cost (Undiscounted)	32,964.38 M$

F. CHAPTER SUMMARY

This chapter demonstrates how the architecture of the ship is translated into a ship design. It discusses how an *Excel* ship synthesis model is used to calculate all the ship characteristics and costs associated with three alternatives. The model uses inputs from a reference ship and the desired parameters captured from the mission effectiveness model.

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VI. DESIGN SPACE ANALYSIS

The data collected from each alternative (including the baseline alternative) has been plotted to illustrate the tradeoffs in terms of cost, weight, radar detection range, and probability of survival.

A. SHIP DESIGN VERSUS CAPABILITY

Weight as an element of ship design is influenced in a linear fashion by the radar system selection, which represents the mission capability. Figure 19 shows three data points that represent the three alternative ship designs. The relationship between the variables weight and radar detection range is linear. Therefore, the slope of the trendline represents the cost of every additional kilometer of detection range. A kilometer of additional radar detection range impacts the weight with 0.0478 ltons.

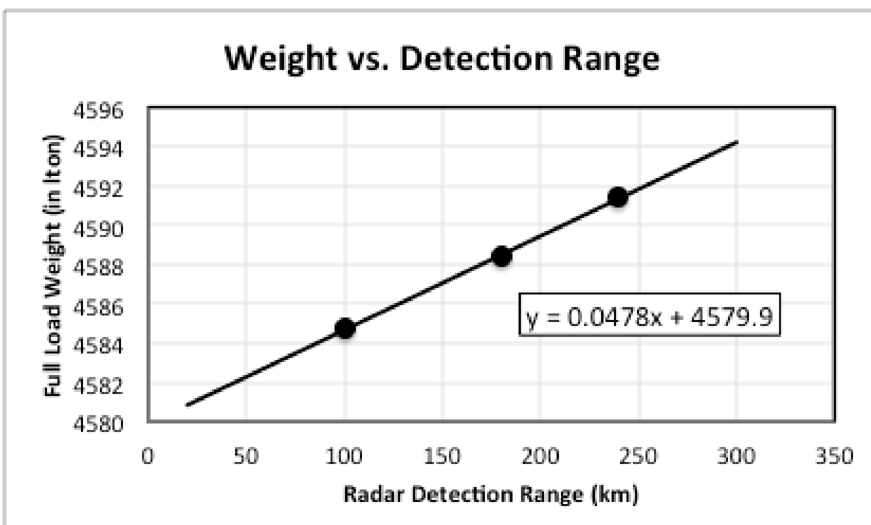

Figure 19. Weight vs. Detection Range Graph

Figure 20 shows the tradeoff that you have in terms of weight for the increased capability in the AAW scenario. A ship to be designed with a probability of survival that

is approximately 0.5 greater than the baseline will weigh an estimated 3.7 ltons more. Yet, to add on the last 0.08 to the probability of survival adds an additional 3 ltons to the total weight.

Decision makers should consider whether or not they want to add 3.7 ltons to the baseline design for 0.5 increase in probability of survival or add nearly twice that much weight and get 0.58 increase.

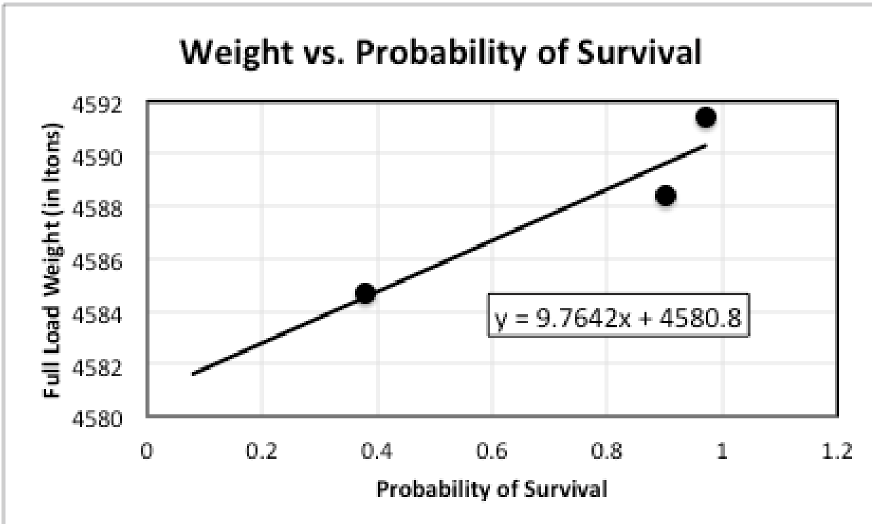

Figure 20. Weight vs. Probability of Survival Graph

B. COST VERSUS CAPABILITY

Figure 21 shows that a linear relationship exists between the total end cost of a ship and the radar detection range. The slope of the trendline indicates that the cost of every additional kilometer in range costs $20,000. The purchase price of every kilometer of additional radar range comes out to be $20,000

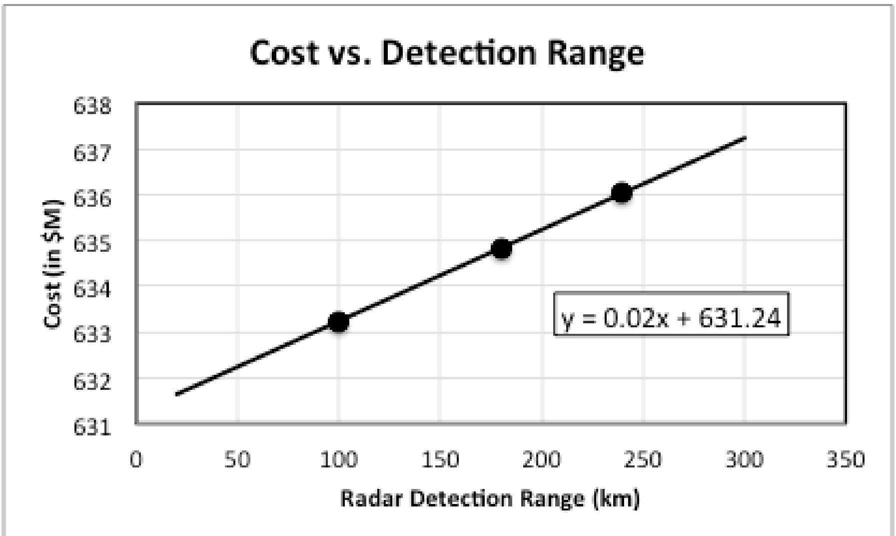

Figure 21. Cost vs. Detection Range Graph

Figure 22 shows that relationship between capability and cost is not linear. Essentially, it costs $1.6 million for an increase in capability of 0.5 but it costs $1.2 million for the additional 0.08 capability of alternative 3.

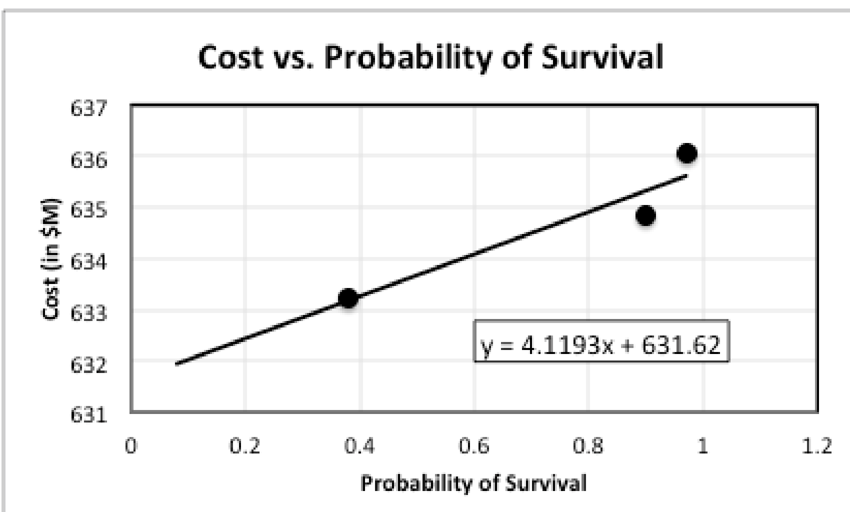

Figure 22. Cost vs. Probability of Survival Graph

The slope between the first two data points (alternative one and alternative two), is 3.08 which (when multiplied by 0.01) indicates that the cost of adding 0.1 to the probability of survival is $30,800. Whereas, an increase in probability of survival by 0.1 from the second alternative to the third is approximatly $171,400, which is approximately a 460% increase in the price of 0.1 probability of survival.

The decision to be made is how important is it to have a probability of survival at 98%. Is it worth the tradeoff in cost and in weight?

C. CHAPTER SUMMARY

This chapter demonstrated how the proposed ship design method incorporates a synthesis model to reveal the tradeoffs of cost vs. capability and ship design vs. capability. The results of the effectiveness model showed the impact that an individual system characteristic (air search radar detection range) had on the MOE. This section also shows how that characteristic translates to cost and overall ship design.

VII. CONCLUSIONS AND RECOMMENDATIONS

This thesis proposed a method for combatant ship design using MBSE. That is, simulation models were elevated to a central and governing role in the specification and design of a naval surface combatant.

A. SUMMARY

Notionally, the U.S. Navy has a need for a surface combatant that could perform a particular mission, independent power projection in the Yellow Sea. This need was interpreted and a DRM was developed outlining the mission profile, operational environment, threats, measures of performance, and system requirements. It was determined that there was a threat of attack by ASM with characteristics similar to that of a French Exocet missile. The ship needs to be able to complete this mission without being resupplied for up to a month and defend itself against the airborne attack.

From that DRM, the architecture was developed for a ship in terms of functions and physical components. The architecture was then modeled to show how the ship would behave in a particular situation, AAW mission scenario. A mission effectiveness model was created using the architecture and behavior model as a reference. This model showed how individual system specifications (air search radar detection range) impact the effectiveness of the ship in the AAW mission.

Then the ship was synthesized using a reference ship as a starting point and incorporating a variety of radar detection ranges to reveal the relationships between cost, ship design, and capability. A trade space using actual feasible ship designs and estimated costs was created to reveal the tradeoffs of improving capability.

B. CONCLUSIONS

This work addressed several questions regarding MBSE and system architecture development and how they contribute to improving the outcome of the combatant ship design process. These questions and their answers are discussed:

Can a structured model-based approach to ship design provide a consistent basis for connecting capability need to the end solution? MBSE tools such as *CORE* provide for identification and mapping of interfaces, mapping of needs to requirements to solutions, and provide a cohesive and consistent system model upon which to base the design process. A solution neutral functional architecture was developed through to reveal the functions necessary to satisfy the stakeholder's needs. As assumed for the purposes of demonstration, the physical architecture alternative for a ship was selected for exploration of behavior and mission effectiveness. With physical components mapped to the functional architecture linking the physical architecture to the capability need, an EFFBD was created to model the logical behavior of these functions as performed by the physical components. The EFFBD, in part, helps to determine design specifications necessary to satisfactorily meet the capability need as well as identify limitations and/or constraints existing in the physical architecture (demonstrated by a resource-monitoring simulation of the EFFBD within *COREsim*). Also aiding in the identification of design specifications is DES modeling of the mission scenario in *ExtendSim* to capture mission effectiveness across varying input parameters. The *ExtendSim* model reflects the behavior logic described in the EFFBD, therefore simulates the performance of the system described by the functional and physical architectures. The *ExtendSim* model links to the capability need through the physical architecture and the EFFBD. The design alternatives created reflect the identified design specifications from the EFFBD, *ExtendSim* model, and physical architecture. Thus, the link between capability need and end solution (ship synthesis) is made through a functional architecture description, the physical architecture of a ship, behavioral modeling, and mission effectiveness modeling.

How can a ship be designed effectively in terms of performance and effectiveness related to mission capabilities? Effectiveness in the design process can be enhanced through the use of MBSE tools. By elevating models to a central and governing role in the specification, design, integration, and validation, the system performance can be simulated for future threat environments. MBSE was used to demonstrate how the

quantitative results of a tradeoff between ship characteristics, such as displacement and cost, and mission effectiveness can be used to reason about the engineering possibilities involved.

In what ways can modeling tools promote the creation of the right design solution in terms of performance and effectiveness related to mission capabilities? Enhancing the traceability between steps of the design process will help to ensure the validity of the design solution. The right design solution is ensured by linking it to the mission effectiveness model, behavioral model, physical architecture, functional architecture, and finally to the capability needs.

How can MBSE be used to enhance traceability throughout a combatant ship design process to produce a valid trade-space for decision-makers? This thesis shows that MBSE can be used to aide designers and decision-makers in developing a solution that meets their needs while being aware of the tradeoffs early in the conceptual design phase. The analysis performed through *ExtendSim*, *CORE*, and ship synthesis reveals significant considerations between cost, capability, and design.

C. RECOMMENDATIONS FOR FURTHER RESEARCH

Further research in this area includes development of a more complex DRM that would demonstrate how a multi-mission ship would go through these design steps. That would require that multiple behavioral models and mission effectiveness models be created. Also, more research could be done in the area of individual system characteristics that might impact the MOE. For instance, in this thesis as well as in that of Welch (2011), the characteristic evaluated was air search radar detection range. Further research could evaluate the impact of weapon load out in a more complex AAW scenario.

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APPENDIX A. COMPLETE FUNCTIONAL HIERARCHY

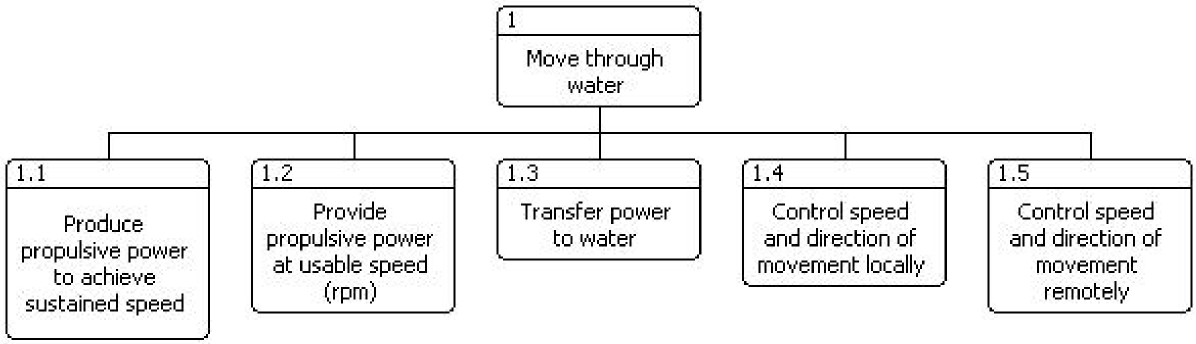

Figure 23. Second-level Functional Decomposition of Function 1

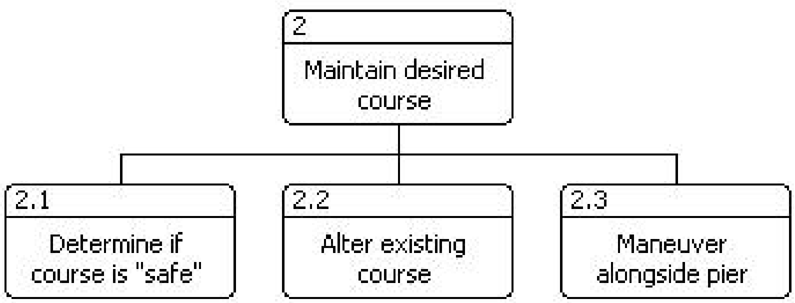

Figure 24. Second-level Functional Decomposition of Function 2

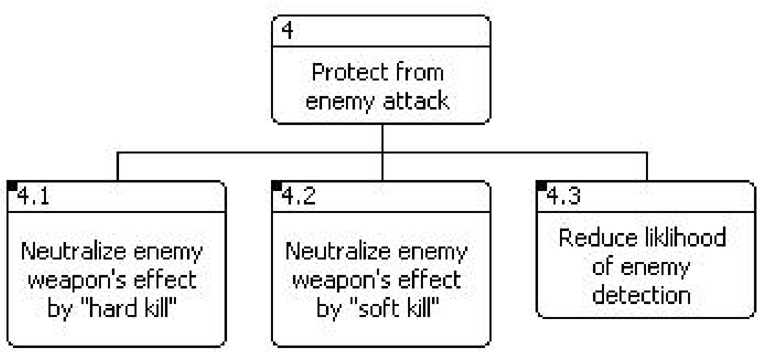

Figure 25. Second-level Functional Decomposition of Function 4

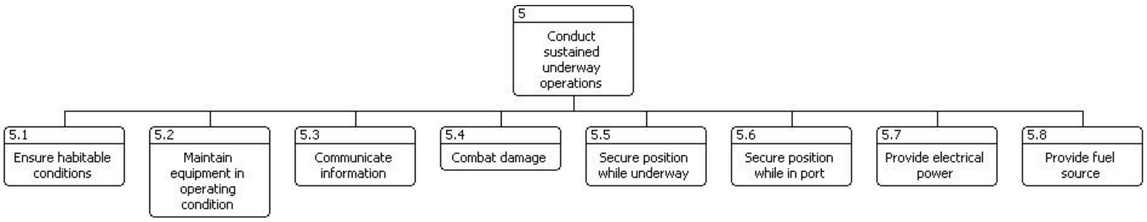

Figure 26. Second-level Functional Decomposition of Function 5

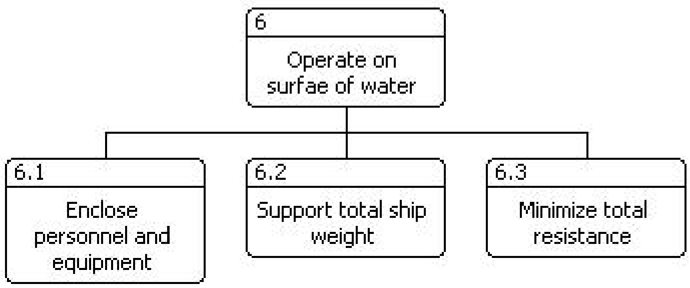

Figure 27. Second-level Functional Decomposition of Function 6

APPENDIX B. COMPLETE TABLE OF FUNCTIONS MAPPED TO PHYSICAL COMPONENTS

Table 18. Complete List of Functions Mapped to Physical Components

Number	Function	Component
0	Perform Surface Combatant Missions	0 Ship
1	Move through water	1 Propulsion system
1.1	Produce propulsive power to achieve sustained speed	1.1 Main propulsion engines (MPE)
1.2	Provide propulsive power at usable speed (rpm)	1.2 Reduction gear
1.3	Transfer power to water	1.3 CRP propeller
1.4	Control speed and direction of movement locally	1.4 Engineering operations station (EOS)
1.5	Control speed and direction of movement remotely	1.5 Lee helm
2	Maintain desired course	2 Maneuvering and control system
2.1	Determine if course is "safe"	2.1 Navigation equipment
2.2	Alter existing course	2.2 Rudder
2.3	Maneuver alongside pier	2.3 Bow thrusters/APU's
3	Neutralize enemy targets	3 Combat systems configuration
3.1	Detect targets	3.1 Ship's sensors
3.1.1	Detect surface and shore based targets	3.1.1 Surface search radar (2D)
3.1.1.1	Switch between transmit/ receive modes	3.1.1.1 Duplexer
3.1.1.2	Transmit/ receive EM pulses	3.1.1.2 Antenna
3.1.1.3	Process EM data	3.1.1.3 Computer
3.1.1.4	Display contacts	3.1.1.4 Radar repeater screen
3.1.1.5	Receive electrical power	3.1.1.5 Electrical hardwire connection point
3.1.1.6	Energize/ de-energize	3.1.1.6 Control panel
3.1.2	Detect subsurface targets	3.1.2 Sonar
3.1.2.1	Detect subsurface contacts without additionally compromising position	3.1.2.1 Passive sonar (towed array "tail")

Number	Function	Component
3.1.2.2	Detect subsurface contacts with compromising position	3.1.2.2 Active sonar (sonar dome)
3.1.3	Detect airborne targets	3.1.3 Air search radar (3D)
3.1.3.1	Switch between transmit/ receive	3.1.3.1 Duplexer
3.1.3.2	Transmit/ receive EM pulse	3.1.3.2 Antenna
3.1.3.3	Process EM data	3.1.3.3 Computer
3.1.3.4	Display contacts	3.1.3.4 Radar repeater screen
3.1.3.5	Receive electrical power	3.1.3.5 Electrical hardwire connection point
3.1.3.6	Energize/ de-energize	3.1.3.6 Control point
3.1.4	Detect electromagnetic (EM) emissions	3.1.4 Electronic countermeasures (ECM) surveillance antennas
3.1.4.1	Filter/ process (amplify) EM data received	3.1.4.1 Computer
3.1.4.2	Display EM data	3.1.4.2 ECM display screen
3.1.4.3	Receive electrical power	3.1.4.3 Electrical hardwire connection point
3.1.4.4	Energize/de-energize	3.1.4.4 Control panel
3.2	Classify targets	3.2 Surveillance systems with identification protocols
3.2.1	Classify surface and airborne targets electronically	3.2.1 Identification friend/ foe (IFF) system
3.2.1.1	Receive IFF signal	3.2.1.1 IFF antenna
3.2.1.2	Interpret IFF signal	3.2.1.2 Computer with database
3.2.1.3	Display IFF signal data	3.2.1.3 IFF display screen
3.2.1.4	Receive electrical power	3.2.1.4 Electrical hardwire connection point
3.2.1.5	Energize/de-energize	3.2.1.5 Control panel
3.2.2	Classify subsurface targets	3.2.2 Passive sonar signature identification protocol
3.2.3	Classify EM emissions	3.2.3 EM signature identification library
3.2.3.1	Receive EM emissions data	3.2.3.1 Transfer protocol
3.2.3.2	Interpret EM emissions comparing to stored library	3.2.3.2 Computer
3.2.3.3	Display classification data	3.2.3.3 ECM display screen

Number	Function	Component
3.2.3.4	Receive electrical power	3.2.3.4 Electrical hardwire connection point
3.2.3.5	Energize/ de-energize	3.2.3.5 Control panel
3.3	Engage targets	3.3 Weapon systems
3.3.1	Engage long range surface/ shore based targets	3.3.1 Surface to surface/ land attack missile system (Tomahawk)
3.3.1.1	Store missiles	3.3.1.1 Canisters (VLS cells)
3.3.1.2	Activate launching system	3.3.1.2 Targeting transfer protocol
3.3.1.3	Launch missiles	3.3.1.3 Missile launch switch
3.3.1.4	Guide missiles to target	3.3.1.4 Guidance system (integral to missile)
3.3.1.5	Track missile's trajectory	3.3.1.5 Missile system fire control radar
3.3.1.6	Allow simultaneous launches	3.3.1.6 Computer
3.3.1.7	Receive electrical power	3.3.1.7 Electrical hardwire connection point
3.3.1.8	Energize/ de-energize	3.3.1.8 Control panel
3.3.2	Engage short range surface/ shore based targets	3.3.2 Naval gun
3.3.2.1	Support gun operations	3.3.2.1 Gun support features
3.3.2.2	Activate firing system	3.3.2.2 Targeting transfer protocol
3.3.2.3	Maneuver gun in to firing position	3.3.2.3 Gun hydraulic system
3.3.2.4	Fire gun	3.3.2.4 Gun firing switch
3.3.2.5	Track projectile's trajectory	3.3.2.5 Gun fire control radar
3.3.2.6	Receive electrical power	3.3.2.6 Electrical hardwire connection
3.3.2.7	Energize/ de-energize	3.3.2.7 Control power
3.3.3	Engage subsurface targets	3.3.3 Torpedo and depth charge delivery system
3.3.3.1	Support torpedo operations	3.3.3.1 Torpedo support features
3.3.3.2	Charge torpedo for launch	3.3.3.2 Breach
3.3.3.3	Launch torpedoes	3.3.3.3 Torpedo launch switch
3.3.3.4	Guide torpedo to target	3.3.3.4 Guidance system integral to torpedo
3.3.3.5	Track torpedo's trajectory	3.3.3.5 Passive sonar
3.3.3.6	Receive electrical power	3.3.3.6 Electrical hardwire connection point
3.3.3.7	Energize/ de-energize	3.3.3.7 Control panel

Number	Function	Component
3.3.4	Engage airborne targets	3.3.4 Surface to air missile system
3.3.4.1	Store missiles	3.3.4.1 Canister (VLS cells)
3.3.4.2	Activate launching system	3.3.4.2 Targeting transfer protocol
3.3.4.3	Launch missiles	3.3.4.3 Missile launch switch
3.3.4.4	Track missile's flight path	3.3.4.4 Missile fire control radar
3.3.4.5	Guide missile to target	3.3.4.5 Illuminators
3.3.4.6	Allow simultaneous launches	3.3.4.6 Computer
3.3.4.7	Receive electrical power	3.3.4.7 Electrical hardwire connection point
3.3.4.8	Energize/ de-energize	3.3.4.8 Energize/ de-energize
3.4	Operate as "node" sharing information within super system	3.4 Combat systems networking protocol (NTDS, JMCIS, etc.)
3.4.1	Transmit target information	3.4.1 Transmit protocol
3.4.2	Receive target information	3.4.2 Receive protocol
3.5	Provide target prosecution flexibility	3.5 Embarked helicopter
4	Protect from enemy attack	4 Countermeasures methods
4.1	Neutralize enemy weapon's effect by "hard kill"	4.1 Self defense weapons
4.1.1	Neutralize long range airborne weapon (missile)	4.1.1 Long range surface to air missile system (NATO Sea Sparrow)
4.1.1.1	Store missiles	4.1.1.1 Canisters (VLS cells)
4.1.1.2	Activate launching system	4.1.1.2 Targeting transfer protocol (4.1.1.2)
4.1.1.3	Launch missiles	4.1.1.3 Missile launch switch
4.1.1.4	Track missile's flight path	4.1.1.4 Missile fire control radar
4.1.1.5	Guide missile to target	4.1.1.5 Illuminators
4.1.1.6	Allow simultaneous launches	4.1.1.6 Computer
4.1.1.7	Receive electrical power	4.1.1.7 Electrical hardwire connection point
4.1.1.8	Energize/ de-energize	4.1.1.8 Control panel
4.1.2	Neutralize medium range airborne weapon (missile)	4.1.2 Medium range surface to air missile system (RAM)
4.1.2.1	Store missiles	4.1.2.1 Canisters (RAM cells)
4.1.2.2	Activate launching system	4.1.2.2 Targeting transfer protocol
4.1.2.3	Launch missiles	4.1.2.3 Missile launch switch
4.1.2.4	Guide missiles to target	4.1.2.4 Infrared guidance system integral to missile
4.1.2.5	Track missile's flight trajectory	4.1.2.5 Missile fire control radar

Number	Function	Component
4.1.2.6	Allow simultaneous launches	4.1.2.6 Computer
4.1.2.7	Receive electrical power	4.1.2.7 Electrical hardwire connection point
4.1.2.8	Energize/de-energize	4.1.2.8 Control panel
4.1.3	Neutralize short range airborne weapon (missile)	4.1.3 Close in weapons system (CIWS)
4.1.3.1	Store projectiles	4.1.3.1 Integral storage bin
4.1.3.2	Activate firing system	4.1.3.2 Automatic arming switch
4.1.3.3	Track target and projectile's trajectory	4.1.3.3 integral fire control radar
4.1.3.4	Guide projectiles to target	4.1.3.4 Projectile-target position matching protocol
4.1.3.5	Fire projectiles until target destroyed	4.1.3.5 Computer
4.1.3.6	Receive electrical power	4.1.3.6 Electrical hardwire connection point
4.1.3.7	Energize/ de-energize	4.1.3.7 Control panel
4.2	Neutralize enemy weapon's effect by "soft kill"	4.2 self defense decoys
4.2.1	Neutralize acoustic targeted weapons	4.2.1 Deployable noisemakers (Nixie)
4.2.1.1	Hold noisemaker	4.2.1.1 Canister
4.2.1.2	Charge noisemaker for launch	4.2.1.2 Breach
4.2.1.3	Launch noisemaker	4.2.1.3 Noisemaker launch switch
4.2.1.4	Track noisemaker's trajectory	4.2.1.4 Passive sonar
4.2.1.5	Receive electrical power	4.2.1.5 Electrical hardwire connection point
4.2.1.6	Energize/ de-energize	4.2.1.6 Control panel
4.2.2	Neutralize home on EM weapons	4.2.2 Electronic countermeasures (ECCM)
4.2.2.1	Determine EM frequency being targeted	4.2.2.1 Computer
4.2.2.2	Select respective EM frequency to be jammed	4.2.2.2 Frequency selection protocol
4.2.2.3	Jam respective EM spectrum range	4.2.2.3 Antenna emitting high intensity EM pulse

Number	Function	Component
4.2.2.4	Receive electrical power	4.2.2.4 Electrical hardwire connection point
4.2.2.5	Energize/ de-energize	4.2.2.5 Control panel
4.2.3	Neutralize home on IR weapons	4.2.3 Deployable IR decoys (Torch)
4.2.3.1	Hold decoy	4.2.3.1 Canister
4.2.3.2	Launch decoy	4.2.3.2 IR decoy launch switch
4.2.3.3	Receive electrical power	4.2.3.3 Electrical hardwire connection point
4.2.3.4	Energize/ de-energize	4.2.3.4 Control panel
4.2.4	Neutralize home on object weapons	4.2.4 Deployable false targets (Chaff)
4.2.4.1	Hold false target	4.2.4.1 Canister
4.2.4.2	Launch false target	4.2.4.2 Chaff launch switch
4.2.4.3	Receive electrical power	4.2.4.3 Electrical hardwire connection point
4.2.4.4	Energize/ de-energize	4.2.4.4 Control panel
4.3	Reduce likelihood of enemy detection	4.3 Signatures reduction
4.3.1	Reduce detection by acoustic sensing means	4.3.1 Acoustic masking and vibration damping
4.3.1.1	Mask propeller noise	4.3.1.1 Prairie system
4.3.1.2	Mask hull noise	4.3.1.2 Masker system
4.3.1.3	Absorb vibrations	4.3.1.3 Vibration absorbent decks (rubber matting)
4.3.1.4	Absorb engine vibrations (specifically)	4.3.1.4 Vibration absorbent mounts
4.3.2	Reduce detection by electromagnetic (EM) sensing means	4.3.2 Exploitation of radar EM pulse characteristics
4.3.2.1	Minimize radar cross section (RCS)	4.3.2.1 Superstructure construction
4.3.2.2	Cause radar EM pulse to not return to source	4.3.2.2 Radar absorbent material (RAM) applied to superstructure
4.3.3	Reduce detection by infrared (IR) sensing means	4.3.3 Dissipation of heat source
4.3.3.1	Dissipate engine exhaust heat	4.3.3.1 Stack boundary layer infrared suppression system (BLISS)
4.3.3.2	Dissipate general space heat	4.3.3.2 Ventilation insulation
4.3.4	Reduce detection by EM surveillance means	4.3.4 EM radiation control (EMCON conditions)

Number	Function	Component
4.3.5	Reduce detection by magnetic field actuated ordnance	4.3.5 Degaussing system
4.3.5.1	Input magnetic signature adjustments	4.3.5.1 Degaussing control station
4.3.5.2	Adjust transverse magnetic signature	4.3.5.2 M-Coil
4.3.5.3	Adjust longitudinal magnetic signature	4.3.5.3 L-Coil
4.3.5.4	Adjust vertical magnetic signature	4.3.5.4 P-Coil
5	Conduct sustained underway operations	5 Support/Auxiliary systems
5.1	Ensure habitable conditions	5.1 Crew support/ habitability features
5.2	Maintain equipment in operating condition	5.2 Maintenance philosophy
5.3	Communicate information	5.3 Communications equipment
5.4	Combat damage	5.4 Damage control (DC) systems and equipment
5.5	Secure position while underway	5.5 Anchoring system
5.6	Secure position while in port	5.6 Mooring system
5.7	Provide electrical power	5.7 Electrical system
5.8	Provide fuel source	5.8 Fuel system
6	Operate on surface of water	6 Hull form
6.1	Enclose personnel and equipment	6.1 Hull
6.2	Support total ship weight	6.2 Displaced hull form volume
6.3	Minimize total resistance	6.3 Hull form characteristics (coefficients of form)

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APPENDIX C. EFFBD

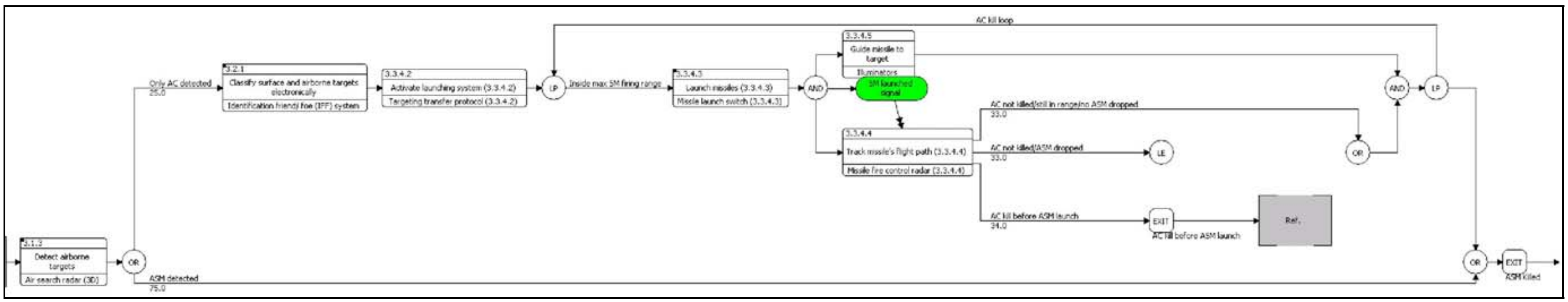

Figure 28. AAW EFFBD (Only aircraft detected branch)

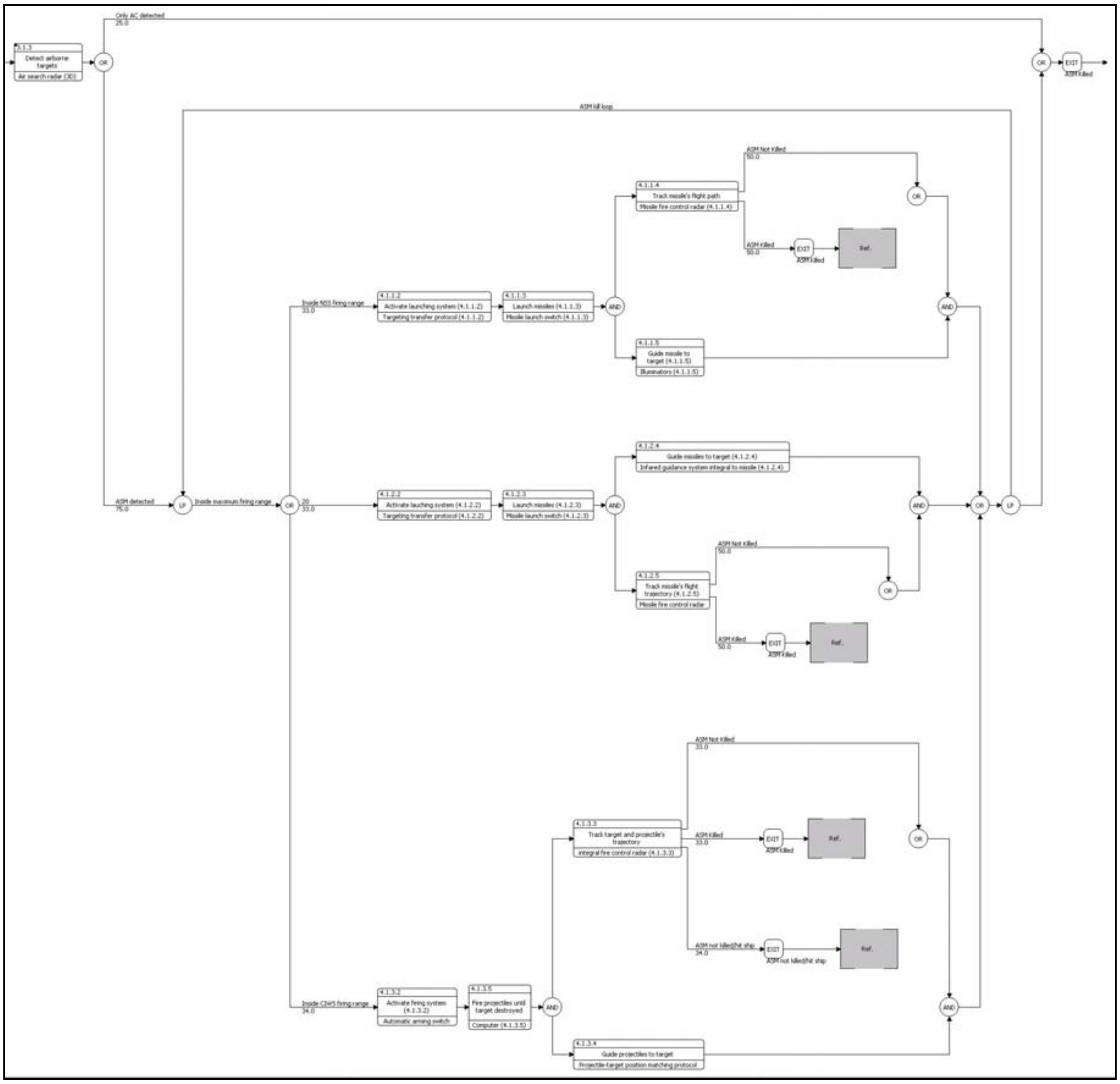

Figure 29. AAW EFFBD (ASM detected branch)

APPENDIX D. EXTENDSIM SCREEN SHOTS

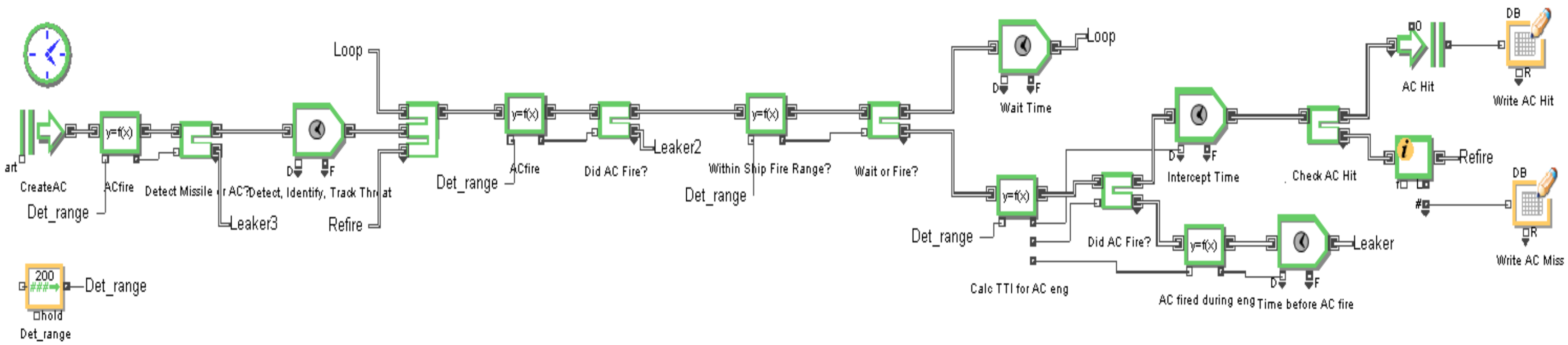

Figure 30. AAW Warfare Effectiveness Model

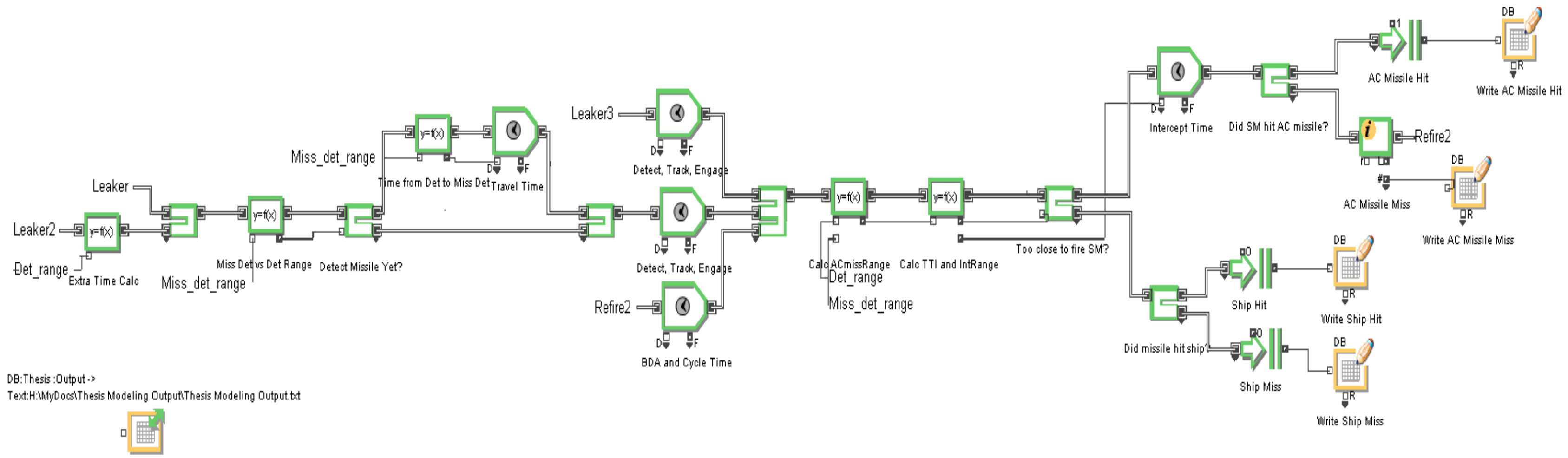

Figure 31. AAW Warfare Effectiveness Model

APPENDIX E. COST ESTIMATION DATA SHEETS

Table 19. Follow Ship Cost Calculation Sheet

Description	Variable	Value	Units
Follow Ship Cost			
Learning Rate Factor	LRF	0.94	
Learning Rate	LR	0.89	
Follow Ship Cost - Shipbuilder Portion			
Follow Ship Basic Construction Cost	CFBCC	115.29	M$
Follow Ship Margin Cost	CFM	11.53	M$
Integration/Engineering Follow Ship Factor	CF800F	0.10	
Integration/Engineering Follow Ship Exponent	CF800E	1.10	
Integration/Engineering	CF800C	21.30	M$
Ship Assembly and Support	CF900C	15.41	M$
Total Follow Ship Construction Cost	CFCC	163.52	M$
Profit	FPROFIT	0.10	
Total Follow Ship Price	PF	179.87	M$
Follow Ship Change Order Factor	FSCOF	0.08	
Change Order Cost	COC	14.39	M$
Total Follow Ship Cost Shipbuilder Portion	CFSB	194.26	M$
Follow Ship Cost - Government Portion			
Follow Ship Other Cost Factor	FSOCF	0.03	
Follow Ship Other Cost	FSOC	4.65	M$
Follow Ship Program Manager's Growth Factor	FPMGF	0.05	
Follow Ship Program Manager's Growth	FPMG	8.99	M$
Follow Ship Combat System GFE CER	FSCSCER	0.30	M$/lton
Follow Ship Ordinance and Electrical GFE (Military Payload GFE)	FCMPG	273.30	M$
Follow Ship HM&E GFE Factor	FHMEGFEF	0.02	
HM&E GFE (Boats, IC)	FCHMEG	3.60	M$
Outfitting Cost Factor	FOCF	0.04	
Outfitting Cost	FCOUT	7.19	M$
Total Follow Ship Government Cost	FCGOV	297.73	M$

Description	Variable	Value	Units
Total Follow Ship End Cost	CFEND	491.99	M$
Follow Ship PSA Cost Factor	CFPSAF	0.05	
Follow Ship PSA Cost	CFPSA	8.99	M$
Total Follow Ship Acquisition Cost	CFA	500.99	M$

Table 20. Life Cycle Cost Calculation Sheet

Description	Variable	Value	Units
Research and Development			
Ship Design and Development			
Ship Design and Development Factor	SDDF	0.10	
Basic Ship Construction Design and Development Factor	BSDDF	0.57	
Government Military Payload Design and Development Factor	MPSDDF	0.07	
Ship Design and Development Cost	CSDD	159.82	M$
Ship Test and Evaluation			
Ship Test and Evaluation Factor	STEF	0.20	
Basic Ship Construction Test and Evaluation Factor	BSTEF	0.50	
Government Military Payload Test and Evaluation Factor	MPSTEF	0.65	
Ship Test and Evaluation Cost	CSTE	355.82	M$
Total Ship Research and Development Cost	CRD	515.64	M$
Investment (less base facilities, unrep, etc.)			
Cost of ships	CSPE	8802.61	M$
Average Ship Cost	CAVG	440.13	M$
Cost of Support Equipment (Shore Based)			
Support Equipment Factor	SEF	0.15	
Cost of Ship Support Equipment	CSSE	1320.39	M$
Cost of Spares and Repair Parts (Shore Supply)			
Spares and Repair Parts Factor	SRPF	0.10	
Cost of Spares and Repair Parts	CISS	880.26	M$
Total Investment Cost	CINV	11003.26	M$
Operations and Support			
Personnel (Pay and Allowances)			
Officer Cost Factor	CFO	0.03	
CPO and Enlisted Cost Factor	CFE	0.02	
Cost of Pay and Allowances	CPAY	4998.36	M$
TAD Factor	TADF	0.00	
Cost of TAD	CTAD	0.67	M$

Description	**Variable**	**Value**	**Units**
Total Cost of Personnel	CPERS	4999.03	M$
Operations			
Number of Operating Hours per Year	H	3018.06	hours
Operations Cost Factor 1	OCF1	188.00	
Operations Cost Factor 2	OCF2	2.23	
Operating Hours Factor		26.90	hours
Operating Hours Cost Factor	OHCF	0.04	1/hours
Average Ship Cost Factor for Operations	ASFCO	0.00	1/$
Government Follow Ship Military Payload Cost Factor	MPGCF	0.01	1/$
Cost of Operations	COPS	1913.42	M$
Maintenance			
Maintenance Cost Factor 1	MCF1	2967.00	
Maintenance Cost Factor 2	MCF2	4.81	
Maintenance Hours Factor		3.05	hours
Maintenance Hours Cost Factor	MHCF	0.33	1/hours
Average Ship Cost Factor For Maintenance	ASFCM	0.01	1/$
Total Maintenance Cost	CMTC	5314.43	M$
Energy			
Fuel Cost	CFUEL	1.15	$/gal
Fuel Rate	FRATE	6.40	lton/hr
Fuel Conversion	FCONV	6.80	lb/gal
Total Fuel Cost	CNRG	1959.96	M$
Replenishment Spares			
Replenishment Spares Cost	CREP	5721.70	M$
Major Support (COH, ROH)			
Major Support Factor 1	MSF1	698.00	
Major Support Factor 2	MSF2	5.99	
Major Support Operating Hours Cost Factor	MSOHF	10.36	
Average Ship Cost Factor	ASCF	0.00	
Cost of Major Support	CMSP	2008.58	M$
Total Operating and Support Cost	COAS	21917.12	M$
Residual Value			

Description	Variable	Value	Units
Residual Value Cost Factor	RVCF	0.50	
Residual Value	RES	555.50	M$
Total Program			
Total Life Cycle Cost (Undiscounted)	CLIFE	32880.52	M$

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